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TECHNICAL NOTE 3982

EXPLORATORY STUDY OF GROUND PROXIMITY EFFECTS ON THRUST

OF ANNULAR AND CIRCULAR NOZZLES

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SUMMARY

Scale-model studies were conducted with annular and circular nozzles to determine the effect of ground proximity on thrust. The studies were made using cold air, various nozzle-to-ground distances, nozzle pressure ratios from 1.16 to 2.71, and several nozzle configurations.

The data show that proximity of the ground to an annular nozzle will cause a thrust augmentation. The thrust for an annular nozzle compared to that of a circular nozzle of equal flow area will be of the order of 50 percent greater for a ratio of nozzle-to-ground distance to the annular nozzle base diameter of 0.2. The nozzle-to-ground distance at which thrust augmentation began (defined as critical nozzle-to-ground distance) was a function of nozzle pressure ratio and the ratio of nozzle flow area to nozzle base area, typical values being of the order of 1.2 to 1.6 times the nozzle base diameter. Thrust augmentation was generally accompanied by an increase in the jet total pressure. This increase in jet total pressure increased with a decrease in nozzle-to-ground distance.

With a circular nozzle the proximity of the ground will cause a decrease in thrust. This thrust reduction is a function of nozzle-to-ground distance, nozzle diameter, and nozzle pressure ratio. The critical nozzle-to-ground distance for a circular nozzle is a function of nozzle pressure ratio. For nozzle pressure ratios of 1.16 and 2.71 the critical nozzle-to-ground distances in terms of the exhaust-nozzle diameter occurred at 0.92 and 0.57 diameter, respectively.

A brief discussion of the significance of these studies and their application to vertically rising aircraft is included.

INTRODUCTION

The apparent alterations of the aerodynamic characteristics of lifting surfaces when flying close to the ground usually termed "ground

effect" have long been known and explained by means of multiplane theory. The ground-effect phenomenon applies both to wing surfaces of conventional aircraft (ref. 1) and rotating lifting surfaces of helicopters (ref. 2) and results in a general augmentation of the lifting capability of the aircraft near the ground. With the advent of vertically rising aircraft employing turbojet engines whose jet streams may impinge on the ground, an evaluation of the ground effect on the thrust obtained from a nozzle directed perpendicularly to the ground is required.

Experience has shown that the proximity of the ground to a jet stream directed perpendicularly to the ground may result in either a thrust reduction or a thrust augmentation depending on the nozzle configuration employed and the distance from the nozzle to the ground. For a conventional circular exhaust nozzle, such as used in tail-sitting vertical-takeoff-and-landing aircraft, the proximity of the ground to the nozzle produces a reduction in thrust due to ground interference effects at the nozzle; consequently, the jet nozzle on an aircraft of this type must be located a sufficient distance above the ground during takeoff and landing to prevent the loss in thrust associated with this ground effect. A similar problem exists for vertical-takeoff aircraft equipped with swivelled exhaust nozzles or rotatable turbojet engines.

For some novel aircraft configurations the use of an annular nozzle may be considered for takeoff and landing operations. Such a nozzle may consist of a centerbody or base plate surrounded by a flow annulus as shown in the following sketch:
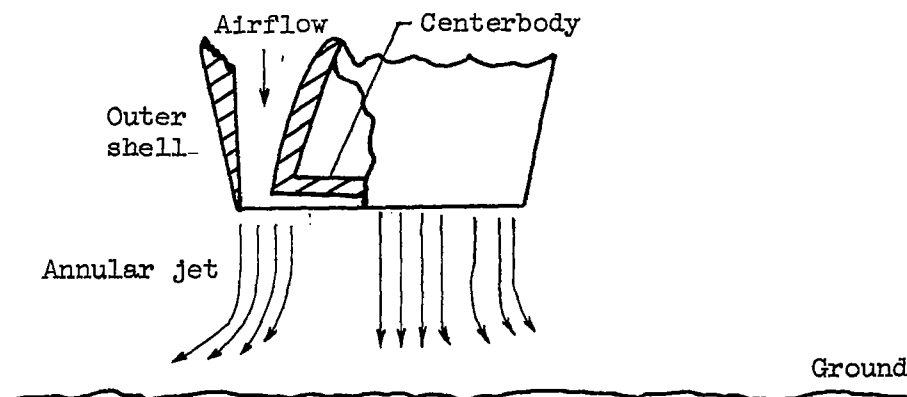
For this nozzle configuration and with the jet stream perpendicular to the ground a thrust augmentation occurs as the nozzle approaches the ground. The total thrust for an annular nozzle near the ground consists of the direct jet thrust and the pressure reaction between the ground and the nozzle base. The thrust augmentation increases as the annular

nozzle comes closer to the ground. An aircraft using such a novel nozzle configuration is not a true vertical-takeoff-and-landing aircraft but may be considered a jet-supported or -cushioned aircraft for takeoff and landing operations.

An exploratory study was conducted at the NACA Lewis laboratory to determine the magnitude of the ground proximity effects on the thrust obtained using circular and annular nozzles when the jet stream is perpendicular to the ground. Data also were obtained to determine the critical distance from the nozzle to the ground (that distance at which thrust changes occur). All these data were obtained with scaled nozzle configurations and cold air but at pressure ratios across the nozzles similar to those used in full-scale engines. An effort was made, within the range of conditions covered in the study, to present the data in parameters useful in applying the data to full-scale nozzle configurations.

SYMBOLS

The following symbols are used herein:

A_b nozzle base plate area, sq in.

A_j jet flow area, sq in. or sq ft as indicated

A_t total nozzle area, $A_j + A_b$, sq in.

D_b diameter of nozzle base plate, in.

D_s inside diameter of outer nozzle shell, in.

F_b thrust due to nozzle base plate, lb

F_L thrust loss, lb

F_t total thrust, lb

G annular gap between outer shell and nozzle base plate, in.

h distance from ground plate to nozzle outer shell, in.

l ground station measured from nozzle centerline, in.

P_j jet total pressure, in. Hg gage lb/in^2

P_n nozzle total pressure, in. Hg abs lb/in^2

p_j' jet static pressure, in Hg abs

p_o atmos pressure, in Hg abs

p_j jet static pressure, in. Hg abs

p_0 atmospheric pressure, in. Hg abs

r_b radius of nozzle base plate, in.

δ distance from end of outer cylindrical shell to nozzle base plate,
        in.

Subscripts:

av   average

cr   critical

o   initial

APPARATUS

Description of Test Facility

Test stand. - A static test stand shown in figure 1 was used to sup-
port the nozzle configurations and obtain thrust measurements. The test
stand consisted of a plenum section (inside diameter, 3 in.; length, 16.5
in.) mounted horizontally on a link-supported force-measuring system.
Cold air was supplied to the plenum by 2.5-inch-inside-diameter twin
supply lines (fig. 2). These lines were located diametrically opposite
one another and at right angles to the plenum in order to eliminate side
and thrust forces caused by the entering air. The lines were also iso-
lated from the force-measuring system by flexible couplings at each end
of the supply lines. A flange to which the nozzles were bolted was pro-
vided at the downstream end of the plenum section.

A 30-inch square metal plate representing the ground (hereafter re-
ferred to as the ground plate) was mounted vertically on a movable plat-
form downstream of the static test stand (fig. 1). The distance from a
nozzle to the ground plate was varied by a remotely controlled motor-
driven screw mechanism on the platform. The distance was determined from
a calibrated counter connected to the screw drive. The angle of the
ground plate to the nozzle axis could be varied manually from 90° to 75°.

Instrumentation. - The airflow through the main air supply line (6-
in. inside diameter) was calibrated by means of vertical and horizontal
total- and static-pressure tube traverses. From this calibration the
pressure indications from a single pitot-static tube mounted in the center
of the main supply line were then sufficient to determine the airflow
during the nozzle tests. Air temperature was measured by copper-
constantan thermocouples located in the plenum section and in the main
air supply line.

The total thrust obtained with the nozzle configurations was measured by strain gages mounted on the link supporting the upstream end of the plenum section (fig. 1). The force measurement from these strain gages was recorded on a modified flight recorder. For the study reported herein the strain gages mounted on the vertical support link were not used except to verify that no vertical forces were incurred that might require consideration in the analysis of the axial-thrust data.

The ground plate was instrumented with flush pressure taps located in the vertical plane. These pressure taps were used to obtain pressure profiles on the ground plate caused by the impinging air from the nozzles.

Miscellaneous equipment. - Photographs of the jet shape, especially in the proximity of the ground, were obtained with a schlieren apparatus. This setup consisted of a single mirror system of conventional design but incorporating a microsecond flash arrangement.

Description of Nozzles

Annular nozzles. - An annular nozzle (fig. 3) consisted of the following primary parts: outer cylindrical shell, centerbody including nozzle base plate, and support struts. The centerbody and one support strut were hollow to permit installation of and access to instrumentation on the nozzle base plate without disturbing the airflow through the annulus. The outer cylindrical shell was adjustable in the axial direction with respect to the centerbody by means of slotted brackets (fig. 3). A pressure seal was used to prevent air leakage between the stationary and movable portions of the outer shell. Several metal rings could be inserted in the annulus as shown in figure 3 in order to vary the flow area at the nozzle exit. Pertinent dimensions of the annular nozzles are summarized in the following table:

Nozzle	Inside diameter of outer shell D_s, in.	Nozzle base diameter, D_b, in.	Jet flow area, A_j, sq in.	Annulus width, G, in.	Ratio of jet flow area to total nozzle area, A_j/A_t
A	5.00 *2.500*	4.16	6.05	0.42	0.31
B	4.75 *2.375*	4.16	4.10	.29	.23
C	4.60 *2.30*	4.16	3.06	.22	.18
D	4.51 *2.15*	4.16	2.35	.17	.15

$\dfrac{t}{R}$ $\dfrac{t}{\frac{1}{2}D_s}$

.168
.098
.078
.067

Pressure taps were located axially along the inside wall of the outer shell and in the vertical plane on the nozzle base plate. In addition, four pressure taps spaced 90° apart were located peripherally around the centerbody near the nozzle exit plane. A single total-pressure probe was mounted just outside the nozzle-exit plane. This latter probe was

adjustable to facilitate measuring the total pressure across the annulus. Three pressure taps were also installed across the blunt end of the outer cylindrical shell.

A special smaller scale annular nozzle shown in figure 4 was used in obtaining schlieren photographs of the jet shape with and without ground effect.

Circular nozzles. - The circular nozzles studied were simple converging nozzles as shown in figure 5 and had the following pertinent dimensions:

Nozzle	Exit diameter, in.	Flow area, A_j, sq in.
E	2.50	4.91
F	2.75	5.94

A total-pressure probe located near the nozzle exit was used to measure the total pressure of the jet stream.

PROCEDURE

Force and pressure data were obtained over a range of nozzle pressure ratios from 1.16 to 2.71. All pressure data were photographically recorded from a multiple-tube manometer and correlated with thrust measurements recorded on the modified flight recorder.

In general, the nozzle pressure ratio across the nozzle during a test was set at a predetermined value and all pressure and thrust data were recorded as the ground plate was systematically advanced toward the nozzle. For most of the studies the ground-plate angle with respect to the nozzle centerline was 90°; however, a limited number of runs were made with ground-plate angles of 85° and 75° from the vertical nozzle axis. Systematic studies for some nozzle configurations were made to determine the effect on thrust of varying the location δ of the exit of the outer shell with respect to the nozzle base plate (fig. 3).

Schlieren photographs illustrating significant characteristics of the jet shape in the proximity of the ground were obtained at nozzle pressure ratios of approximately 1.30, 1.65, and 2.30 for the nozzle shown in figure 4.

RESULTS AND DISCUSSION

The thrust changes caused by the proximity of the ground to the various nozzle configurations are presented in terms of ground proximity

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parameter h/D, thrust parameters F/A and F/AP (proper subscripts defining the specific values used), nozzle area ratios (in terms of A_t, A_j, and A_b as required), and nozzle pressure ratio P_n/p_0. Because of the limited nozzle configurations studied, the parameters and exponential powers used in correlating the data apply directly only over the range of test conditions and nozzles covered in this study. These parameters and exponential powers were obtained empirically and may change somewhat·for a more complete range of variables. Because of the small scale of the models used for this study the pressure gradients and Reynolds number associated with full-scale nozzles may affect the results presented ·herein.

In general the presentation and analysis of the data are divided into five categories: (1) magnitude of the thrust change as a function of nozzle characteristics and distance from the ground to the nozzle, (2) distance of the nozzle from the ground at which a thrust change first occurs (critical distance), (3) effect of ground proximity on the back pressure at the nozzle exit, (4) shape of the ground pressure profile as a function of nozzle characteristics and distance from the ground to the nozzle, and (5) thrust characteristics of the various nozzles without ground effect compared to those calculated theoretically for a conventional circular nozzle.

Annular Nozzles

The thrust for an annular nozzle is assumed herein to consist of the jet thrust and the pressure reaction on the nozzle base plate. The effect of pressure gradients on the internal surfaces of the nozzle centerbody on thrust is neglected. Thrust augmentation for the annular nozzle occurs, therefore, when the pressure forces on the nozzle base are greater than the atmospheric pressure, while thrust losses occur when these pressures are less than the atmospheric pressure.

For an annular nozzle thrust augmentation occurred when the distance from the ground to the nozzle was less than about 1.2 to 1.6 times the nozzle base diameter. The augmentation resulted from a positive pressure buildup on the nozzle base plate as the nozzle approached the ground. Without a ground surface or at nozzle-to-ground distances greater than the critical distance, the thrust of an annular nozzle is less than that of a theoretical circular jet nozzle of equal flow area. The magnitude of thrust augmentation and the critical height of the nozzle from the ground depended on the physical dimensions of the nozzle and the nozzle pressure ratio, as is discussed more fully in later sections of this report. Furthermore, the thrust augmentation with a fixed-exhaust-area annular nozzle was accompanied by an increase in jet total pressure, which for an airplane configuration would constitute a back pressure on

the engine. The increase in jet total pressure due to ground proximity
increased with a decrease in nozzle-to-ground distance.

An indication of the thrust-augmentation possible by means of ground
effect with an annular nozzle is given in figure 6. In this figure
thrust is shown as a function of h/D_b for nozzle configuration A, a
nominal nozzle pressure ratio P_n/p_0 of 2.0, and a δ of 0.125 inch.
The data shown are for two operational means of passing airflow through
the nozzle: (1) maintaining a constant jet total pressure independent of
h/D_b location, and (2) permitting the jet total pressure to increase as
h/D_b decreases, that is, permitting back pressure to build up. In addi-
tion, the theoretical thrust of a circular jet (without ground) of equal
nozzle flow area is also shown for comparison. Thrust augmentation in
the form of an abrupt change in thrust begins at an h/D_b value of about
1.57. With constant jet total pressure the thrust of the annular nozzle
is 16 percent less than that calculated theoretically for a conventional
circular nozzle at h/D_b values greater than critical (or without ground).
At h/D_b values less than critical the thrust of the annular nozzle with
constant pressure ratio is increased over that for the circular nozzle
without ground by 58 percent at an h/D_b of 0.25. Similar results were
obtained for the case of increasing jet total pressure in the annular
nozzle, but the thrust augmentation obtained for a given h/D_b was
slightly larger than that for the case of constant jet total pressure.

Typical photographs of the jet shape issuing from an annular nozzle
are shown in figure 7 for several locations of the ground with respect to
the nozzle exit. The nozzle pressure ratio for the jet shown in these
photographs was approximately 1.65. In figure 7(a) the jet shape without
ground is illustrated. For this condition, as is shown later, negative
pressure with respect to the surrounding atmosphere exists on the nozzle
base plate; consequently, the annular jet stream converges or necks down
behind the nozzle. In figure 7(b) a ground plate has been inserted down-
stream of the nozzle; however, the distance between the nozzle and ground
is still sufficiently great so that no thrust augmentation occurs. In
effect the jet shapes shown in figures 7(a) and (b) are similar. Disper-
sion of the impinging jet on the ground plate is apparent in figure 7(b).
In figure 7(c) the ground plate is sufficiently close to the nozzle to
cause thrust augmentation. The shape of the annular jet is changed and
no longer converges behind the nozzle. Because the pressure on the noz-
zle base plate is now positive with respect to the atmosphere (to be
discussed later), the jet even tends to diverge slightly downstream of
the nozzle exit. The point at which a change in jet shape occurs is
signified by rapid fluctuations of thrust because the jet shape is un-
stable. This jet instability occurs over only a very narrow region, as
is discussed in the following sections. Moving the ground closer to the
nozzle than the distance shown in figure 7(c) results in increased thrust

augmentation and a somewhat wider divergence of the jet downstream of the nozzle. Similar jet shapes were obtained at both higher and lower nozzle pressure ratios than that of figure 7. It is of interest to note that for most of the data obtained with the nozzle type shown in figure 3 sufficient water vapor was condensed out of the air leaving the nozzles to permit easy visualization of the jet shape, which aided in establishing the critical ground-to-nozzle distance at which thrust augmentation began.

The following sections present generalized correlations of the annular-nozzle thrust and flow characteristics in terms of pertinent parameters.

Base plate thrust augmentation. - As previously pointed out, the total thrust of an annular nozzle consists of the thrust of the jet stream and the pressure reaction on the nozzle base plate; the effect of the pressure distribution on the internal surfaces of the centerbody is neglected. Since the force-measuring system measures only total thrust, the thrust augmentation or reduction due to the base pressure reaction was obtained from an integration of the pressure distribution over the nozzle base plate. These data are shown in figure 8 in terms of a thrust parameter $F_b/A_b P_j$ as a function of the ground proximity parameter h/D_b. For a particular nozzle configuration it is apparent that the data may be represented by a single curve. The curve is discontinuous at the point where the jet changes shape with negative values of $F_b/A_b P_j$ indicating thrust reduction and positive values of $F_b/A_b P_j$ indicating thrust augmentation. The precise value of h/D_b at which the jet changes shape and thrust augmentation occurs is a function of nozzle pressure ratio and nozzle configuration, as is discussed later. A thrust parameter value of zero indicates that the pressure on the nozzle base is atmospheric and neither augments nor reduces the thrust obtained from the jet. As the ground surface approaches the nozzle after a change in jet shape has occurred, the thrust parameter increases with decreasing h/D_b values. For nozzle configuration A, a value of $F_b/A_b P_j$ of approximately 0.49 occurs at an h/D_b location of 0.2. The location of the outer shell with respect to the nozzle plate shows no effect on thrust augmentation for δ values of 0, 0.125, and 0.5 inch, as can be seen from a comparison of the data in figures 8(a), (b), and (c). As the ratio of the annular jet area decreases with respect to the nozzle base area (nozzles B and C relative to A), the thrust augmentation at the same h/D_b station decreases (figs. 8(d) and (e)). As the jet-stream annulus becomes extremely thin, it is apparently unable to build up sufficient pressure on the nozzle base plate without the jet deteriorating or spilling near the ground.

The thrust augmentation for an annular nozzle can also be expressed conveniently in terms of the flow area of the jet stream instead of the

In general, good correlation of the data was obtained. However, it was observed that at P_n/p_0 values less than choking (P_n/p_0, 1.89) the data for nozzle configuration D would no longer correlate. Analysis of the pressure data over the nozzle base indicated that for this nozzle configuration the center of the base was at atmospheric pressure. Apparently the jet pressures were insufficient to prevent the deterioration of the jet stream and thereby caused atmospheric pressure to act on some portions of the nozzle base. From these data it would appear that the thrust parameter shown in figure 11 may not be valid for nozzle configurations having A_j/A_b or A_j/A_t ratios smaller than those of configuration D.

The pressures on the blunt end of the outer cylindrical shell indicated negligible base drag contributions over the range of test conditions used herein; consequently, these data measurements were neglected in this analysis.

Critical ground-to-nozzle distance. - The distance from the nozzle to the ground at which thrust augmentation occurred h_{cr} was observed to be a function of ratio of nozzle flow area A_j to total nozzle area A_t, of offset of the outer shell to the nozzle base δ, and of nozzle pressure ratio. For nozzle pressure ratios of 1.8 and greater sufficient water vapor was condensed in the jet stream to permit visual observation of the change in jet stream associated with thrust augmentation, as previously mentioned. In addition, the rapid fluctuations of thrust, as recorded on the strain-gage flight recorder, and the pressure fluctuations on the nozzle base helped to establish the critical distance from the nozzle to the ground at which thrust augmentation started. The h_{cr} value for the various annular nozzle configurations is shown in figure 12 as a function of nozzle pressure ratio. For a specific nozzle the h_{cr} value increases slightly (3 percent) with increasing pressure ratio up to the choking pressure ratio; thereafter the h_{cr} value decreases slightly (about 2.5 percent) with increasing pressure ratio. As the ratio A_j/A_t becomes smaller, h_{cr} occurs nearer the nozzle. In terms of nozzle dimensions h_{cr} occurred at about 1.2 to 1.6 times the diameter of the nozzle base plate. Small decreases in h_{cr} also occurred as δ was increased. For nozzle configuration A, a change in δ from zero to 1.0 inch caused a decrease in h_{cr} of about 10 percent at a nozzle pressure ratio of 2.1.

In order to represent the data shown in figure 12 as a single curve a critical-ground-height parameter which contained all the independent variables affecting h_{cr} except nozzle pressure ratio was developed. This parameter $(h/D_b)(1 + 0.67\ \delta/h)(A_t/A_j)^{0.4}$ is shown as a function of nozzle pressure ratio in figure 13. Representation of the data by a single curve is evident, although it is also apparent that completely satisfactory correlation of the data was not achieved by this parameter.
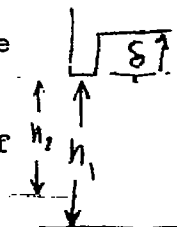
Effect of ground proximity on nozzle pressures. - For h/D_b values less than critical the jet total pressure in the nozzle generally increased as h/D_b decreased. These pressure increases are indicative of a back pressure that would be exerted by the ground on the nozzle configuration or engine. This back pressure would result in a change in the operating curve for an engine. The effect of the back pressure can be compensated for within limits by use of a variable-exhaust-area nozzle or an increase in fuel flow to maintain thrust or both.

The increase in jet pressure P_j with decreasing values of h/D_b is shown in figure 14(a) for nozzle pressure ratios of 1.16 to 2.53. For pressure ratios of the order of 1.20 to 1.50 an increase in total pressure occurs almost immediately after h_{cr} has been attained (h/D_b values of about 1.0). For nozzle pressure ratios greater than 1.50 the total-pressure increase occurs at progressively decreasing h/D_b values. At nozzle pressure ratios appreciably greater than choking the increase in total pressure may not occur until the nozzle is in very close proximity to the ground; for example, at a P_n/p_0 of 2.50 the total-pressure increase starts at an h/D_b value of 0.35. The h/D_b value at which an increase in total pressure or nozzle back pressure occurs is shown in figure 14(b) as a function of P_n/p_0.

As the nozzle approaches the ground plate, an increase in static pressure also occurs in the nozzle. Figure 15 shows a typical plot of average values of the ratio $(p_j/P_n)/(p_j/P_n)_0$ as a function of h/D_b for nozzle configuration A. With no ground plate or before a change in jet shape (h_{cr}) occurs, this ratio is 1.0. The ratio $(p_j/P_n)/(p_j/P_n)_0$ increases for h/D_b values less than critical. For nozzle pressure ratios less than choking the values of $(p_j/P_n)/(p_j/P_n)_0$ at a given value of h/D_b become greater with increasing P_n/p_0 values. For P_n/p_0 values greater than choking, values of $(p_j/P_n)/(p_j/P_n)_0$ at a given value of h/D_b then decrease with an increase in P_n/p_0 and tend to approach the initial ratio of 1.0. An increase in the ratio $(p_j/P_n)/(p_j/P_n)_0$ as h/D_b decreases below the critical values indicates that the jet exit velocity decreases and at pressure ratios above choking becomes less than sonic. The mass flow through the nozzle, however, remains essentially constant under these conditions.

Ground pressure profiles. - Typical pressure fields on the ground are shown in figure 16 as a function of radial distance along the ground measured from the nozzle centerline. The data shown are for nozzle configuration A with nominal nozzle pressure ratios of 1.8 and 2.1. When

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the ground is at a large distance from the nozzle $(h/D_b,\ 2.13)$ and the jet shape is similar to that shown in figure 7(b), the ground pressure profile is that shown at the bottom of figure 16. At an h/D_b of 1.33 and a jet shape similar to that shown in figure 7(c) thrust augmentation has begun, and the ground profile is wider but of smaller magnitude than that at an h/D_b of 2.13. With decreasing h/D_b, the ground profile again becomes narrower downstream of the nozzle, and the pressure increases in the region bounded by the annular jet stream. In addition, a peak pressure occurs where the jet stream impinges on the ground (at l/r_b values of 1.50 and 1.25 for h/D_b values of 0.56 and 0.18, respectively). No significant differences in ground profile are noted for nozzle configuration A with a change in nozzle pressure ratio except for an increase in ground pressure as the nozzle pressure ratio increases. For the same nozzle pressure ratio no significant differences in ground pressure profiles were noted for various annular-nozzle configurations.

Effect of ground incidence angle on thrust augmentation. - A limited study of the effect of ground incidence angle to an annular nozzle showed that the thrust augmentation was reduced with increasing ground incidence angle. The thrust augmentation for nozzle configuration A in terms of the thrust parameter $(F_t/A_jP_j)(A_j/A_t)^{0.15}$ is shown in figure 17 as a function of h/D_b for ground incidence angles of 90°, 85°, and 75° and a nozzle pressure ratio of 2.1. The value of h for the data at a ground incidence angle is the distance from the nozzle base plate center to the ground measured on the jet axis. For a particular value of h/D_b the data show that for a ground incidence angle of 85° the thrust augmentation is about 2 to 5 percent less than that for an angle of 90°. At an incidence angle of 75°, the thrust augmentation is about 11 to 14 percent less than that at 90°.

Thrust characteristics without ground. - The thrust of an annular nozzle without ground effect is less than that for a conventional circular nozzle. The thrust for an annular nozzle is reduced by the negative pressure on the nozzle base plate. A comparison of the thrust obtained experimentally with annular nozzles and that obtained theoretically with a circular nozzle is shown in figure 18. The data, as a function of nozzle pressure ratio, are shown in figure 18(a) in terms of thrust per unit area, while those shown in figure 18(b) are in terms of the dimensionless thrust parameter F_t/A_jP_j. The annular nozzles without ground effect produce about 20 percent less thrust than that calculated theoretically for circular nozzles.

Circular Nozzles

Effect of ground on thrust. - The thrust obtained with a circular nozzle decreased in the proximity of the ground. Figure 19 shows the

thrust parameter $F_t/A_j P_j$ for a circular nozzle in terms of a ground
proximity parameter h/D_s for nozzle pressure ratios of 1.16 to 2.71.
The initial value of $F_t/A_j P_j$ varies with nozzle pressure ratio, as
might be expected from theory. With increasing pressure ratio the ini-
tial thrust parameter decreases. For example, with pressure ratios of
1.16 and 2.71 the initial thrust parameters are 1.67 and 1.34, respec-
tively. For any given pressure ratio the thrust parameter $F_t/A_j P_j$
remains constant as the nozzle approaches the ground until a critical
h/D_s value is reached. For distances less than h_{cr}/D_s the thrust pa-
rameter decreased. With an increase in pressure ratio the critical dis-
tance from the ground to the nozzle at which a thrust loss was obtained
decreased. For example, at a pressure ratio of 1.16 the critical h/D_s
distance occurred at about 0.925, while at a pressure ratio of 2.71 the
critical h/D_s occurred at 0.57. At h/D_s values less than about 0.3
the thrust parameter was not significantly different for the range of
initial pressure ratios covered herein. No photographs of the jet shape
with the circular nozzles in the proximity of the ground were obtained;
hence, possible changes in jet shape due to ground effect could not be
ascertained.

Critical ground distance for initial thrust loss. - From the data of
figure 19 the critical distance from the ground to the nozzle at which a
thrust loss occurs can be determined. Figure 20 shows the critical h/D_s
location at which $F_t/A_j P_j$ starts to decrease as a function of nozzle
total-pressure ratio. For the limited range of nozzle sizes studied it
would appear that the ground effect on the critical h/D_s value is inde-
pendent of nozzle diameter and dependent primarily on nozzle pressure
ratio.

Effect of ground on jet total pressure. - The effect of a ground
surface on jet total pressure as a function of h/D_s is shown in figure
21 for several nozzle pressure ratios. These data show that an increase
in jet total pressure occurs when the nozzle reaches h/D_s values near
the ground. The ground-to-nozzle distance at which this increase in jet
total pressure occurs coincides with that for which the thrust parameter
begins to decrease (fig. 19). The increase in jet total pressure due to
ground effect for the circular nozzle (fixed flow area) is similar to
that discussed for the annular ground nozzle and is indicative of a back
pressure effect on an engine.

Thrust without ground. - The thrust of the circular nozzles in terms
of F_t/A_j and $F_t/A_j P_j$ is shown in figure 22 as a function of nozzle
pressure ratio. Also shown in figure 22 is the theoretical thrust for a
circular nozzle. The data indicate that the experimental nozzles dis-
charging into still air had about a 10-percent loss in thrust compared
to that calculated from theory.

CONCLUDING REMARKS

This exploratory study of the ground proximity effects on exhaust nozzles has shown that, with an annular nozzle operating near the ground, thrust increases up to 50 percent greater than the thrust obtainable with a circular nozzle of equal flow area and without ground effect can be achieved. These large thrust-augmentation values occur at nozzle-to-ground distances about 0.2 times the nozzle centerbody or base diameter. The thrust augmentation, however, is accompanied by an increase in the jet total pressure, this pressure increase constituting a back pressure on the engine. In the application of an annular nozzle to novel aircraft in which the jet stream supports the aircraft weight during takeoff or landing these characteristics of the nozzle must be taken into account. In order to elevate and support the aircraft a reasonable distance above the ground, perhaps 4 to 8 feet, a nozzle with a large base and a relatively small annular slit would be required. Such a nozzle configuration would be achieved by utilizing the lower half of the fuselage for the nozzle base or using delta or circular wing platforms. A variable-area exhaust nozzle would alleviate the problem of back pressure on the engine, at some cost in thrust augmentation, however. The thrust loss associated with operation of an annular nozzle without ground effect is of secondary importance, since the annular nozzle is primarily intended to operate near the ground where the ground effect would more than overcome this thrust loss. For the same engine thrust an aircraft supported by an annular jet stream could conceivably take off from an improved landing strip (perhaps a light-weight steel mesh runway) with a greater payload or fuel capacity than could a conventional tail-sitting vertical-takeoff-and-landing aircraft. The assumption is made, of course, that the incorporation of an annular nozzle for takeoff and landing does not compromise the weight of the aircraft prohibitively.

With a circular nozzle a thrust loss is incurred when the nozzle is in the proximity of a ground surface (about 0.3 times the exhaust-nozzle diameter from the ground at nozzle pressure ratios used on turbojet engines). The ground effect on a circular nozzle will determine to a large degree the minimum ground-to-nozzle distance for an aircraft equipped with a rotatable engine installation. Similarly, for tail-sitting vertical-takeoff aircraft the critical ground-to-nozzle distance will help establish the landing-gear arrangement required in order to utilize maximum engine thrust for takeoff.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, January 18, 1957

REFERENCES

1. Reid, Elliott G.: Applied Wing Theory. McGraw-Hill Book Co., Inc.,
     1932, pp. 166-176.

2. Smith, Charles C., Jr., Lovell, Powell M., Jr., and Bates, William R.:
     Effect of the Proximity of the Ground on the Stability and Control
     Characteristics of a Vertically Rising Airplane Model in the Hover-
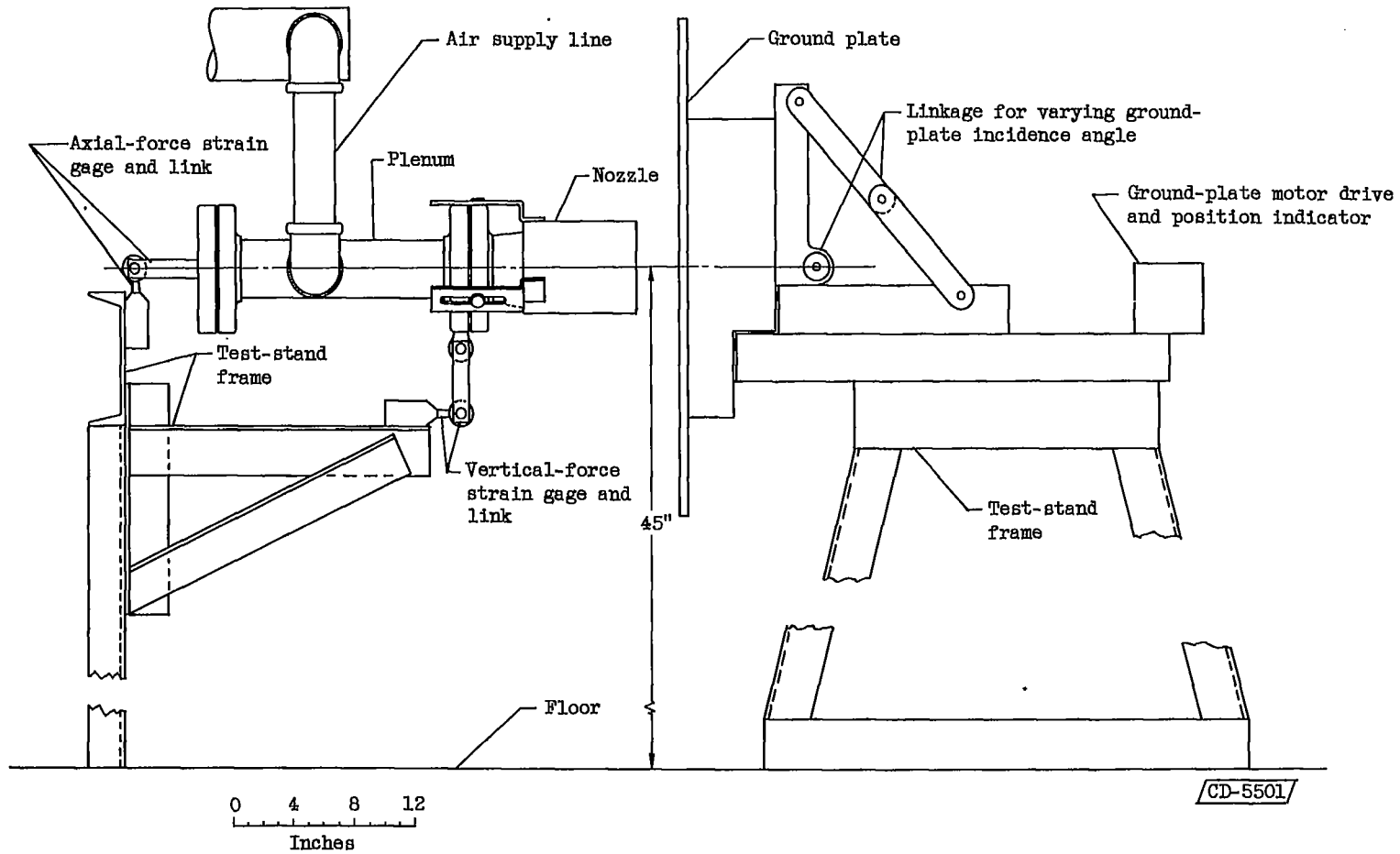   ing Condition. NACA RM L51G05, 1951.

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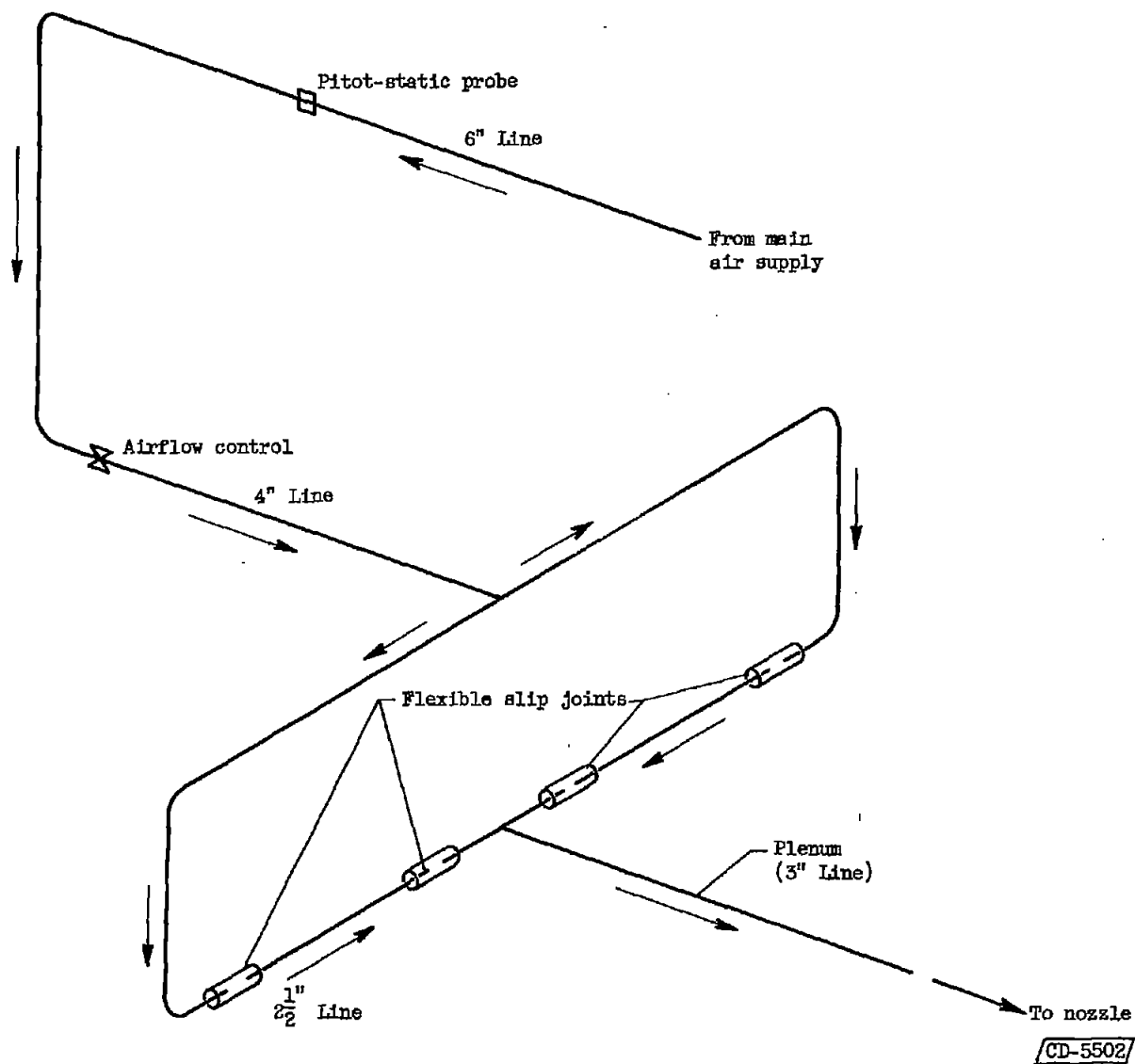Figure 1. - Sketch of setup for annular nozzle and ground plate.
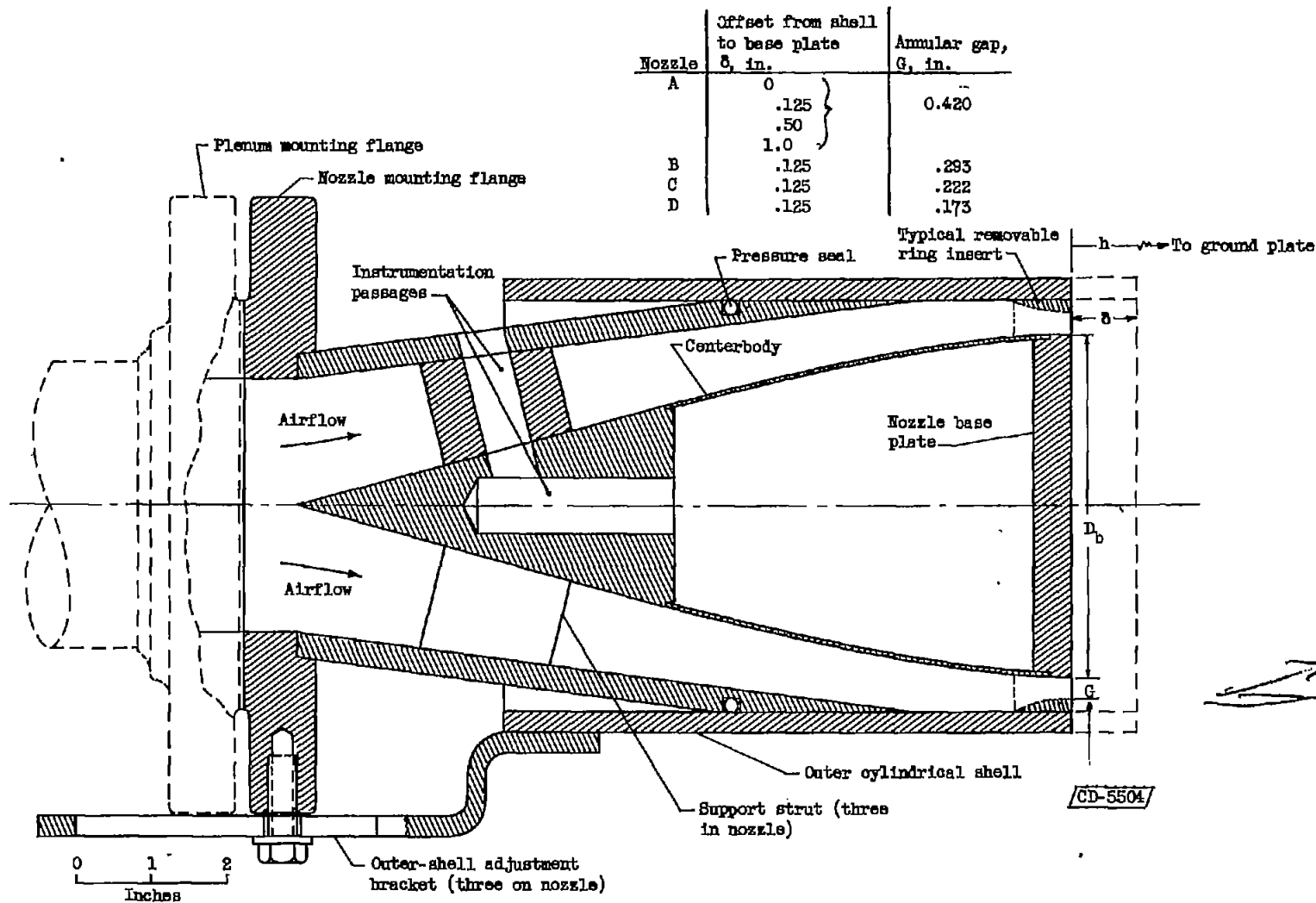
Figure 2. - Schematic diagram of airflow in supply system.

Nozzle	Offset from shell to base plate δ, in.	Annular gap, G, in.
A	0	--
	.125	0.420
	.50	
	1.0	
B	.125	.293
C	.125	.222
D	.125	.173

Plenum mounting flange

Nozzle mounting flange

Pressure seal

Typical removable ring insert

h — To ground plate

Instrumentation passages

Centerbody

δ

Airflow

Nozzle base plate

D_b

Airflow

G

Outer cylindrical shell

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Support strut (three in nozzle)

Outer-shell adjustment bracket (three on nozzle)

0   1   2
Inches

Figure 3. – Sketch of typical annular nozzle.
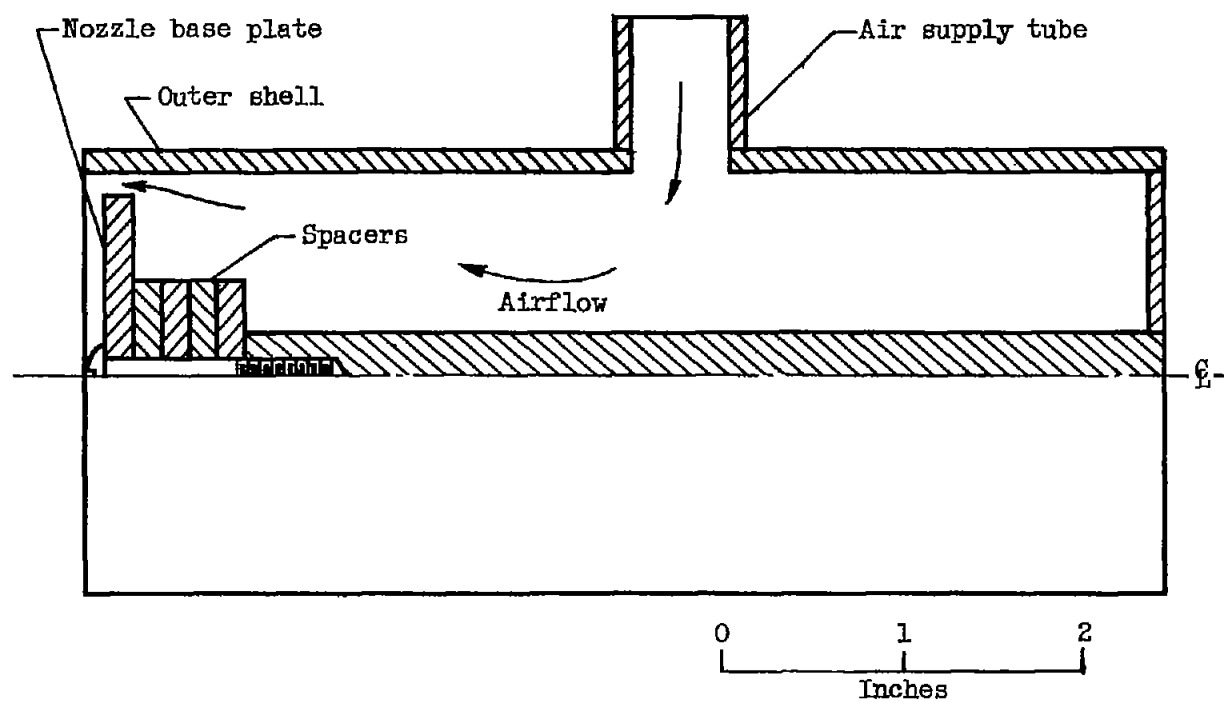
Figure 4. - Annular nozzle used to obtain schleiren photographs of jet shape in proximity of ground.

— Nozzle mounting flange

Nozzle	Inside diameter of nozzle outer shell, D_8, in.
E	2.50
F	2.75

D_8

$\mathfrak{C}$

/CD-5503/

0　　1　　2

Inches
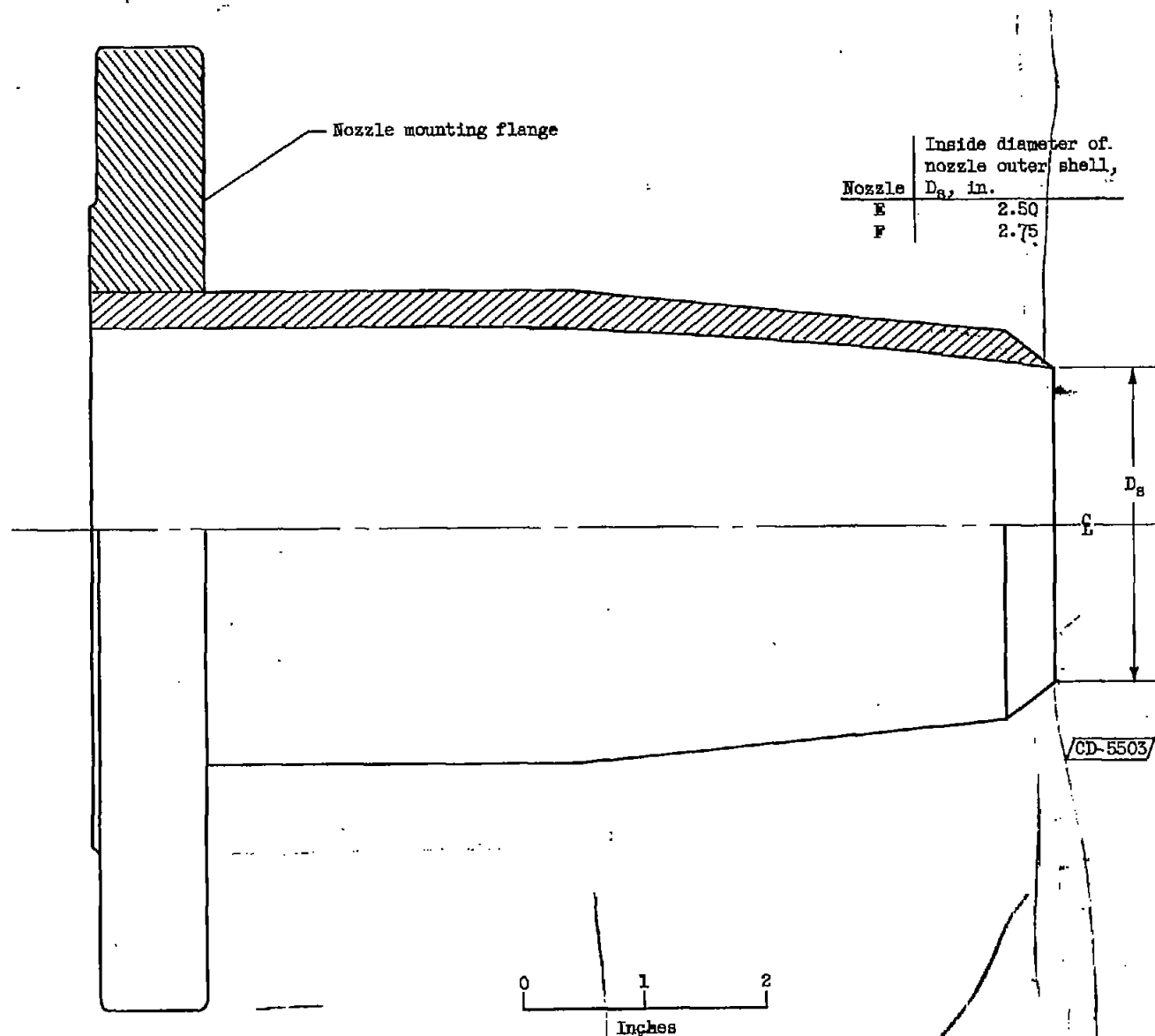
Figure 5. - Cross section of typical circular nozzle.
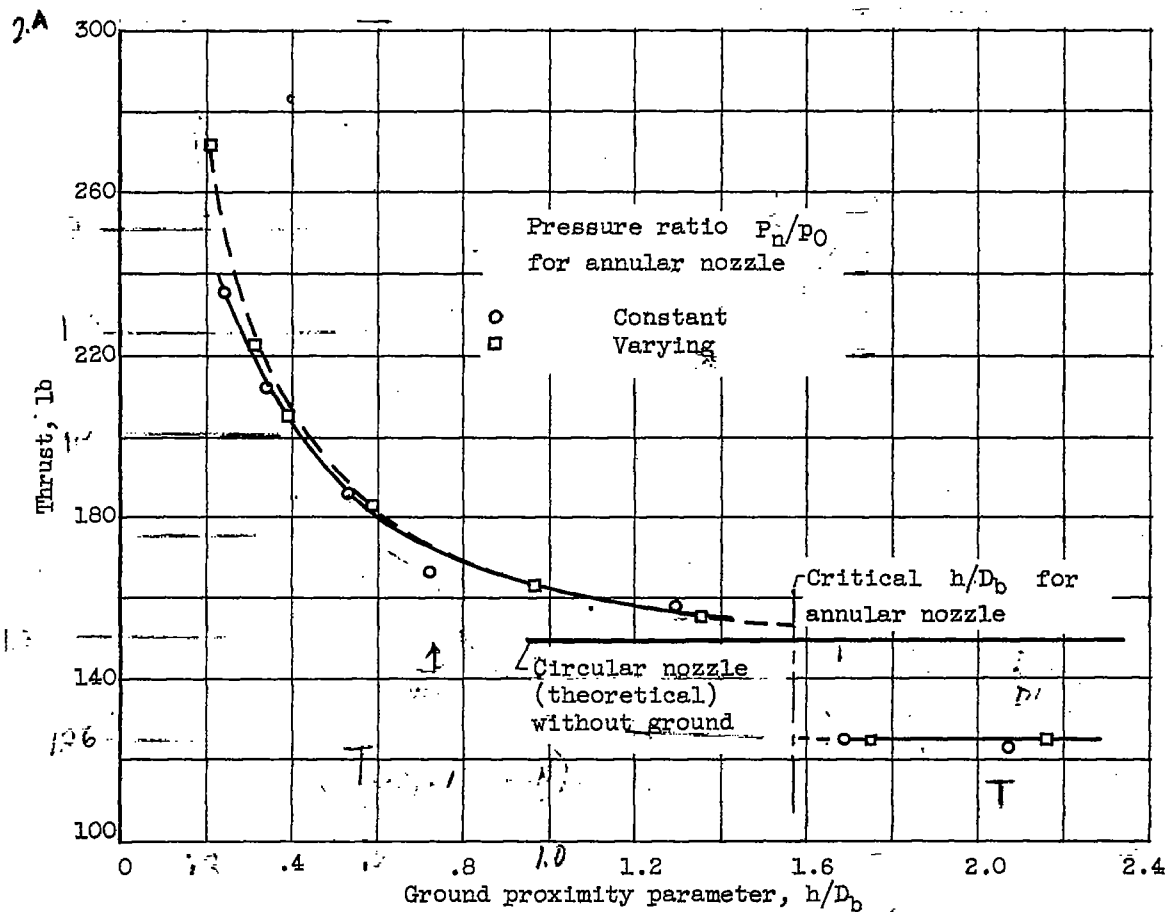
Figure 6. - Typical thrust augmentation obtainable with annular nozzle as function of nozzle-to-ground height. Nozzle configuration, A; initial nozzle pressure ratio, approximately 2.0; offset from shell to base plate δ, 0.125 inch.

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(a) No ground.

(b) With ground; no thrust
augmentation.
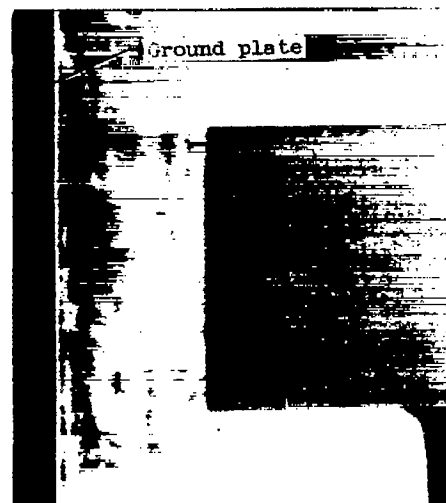
(c) With ground; thrust
augmented.

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Figure 7. - Typical jet shapes as annular nozzle approaches ground. Nozzle pressure
ratio, approximately 1.65.

(a) Nozzle configuration A; offset from shell to base plate δ, 0.

(b) Nozzle configuration A; offset from shell to base plate δ, 0.125 inch.
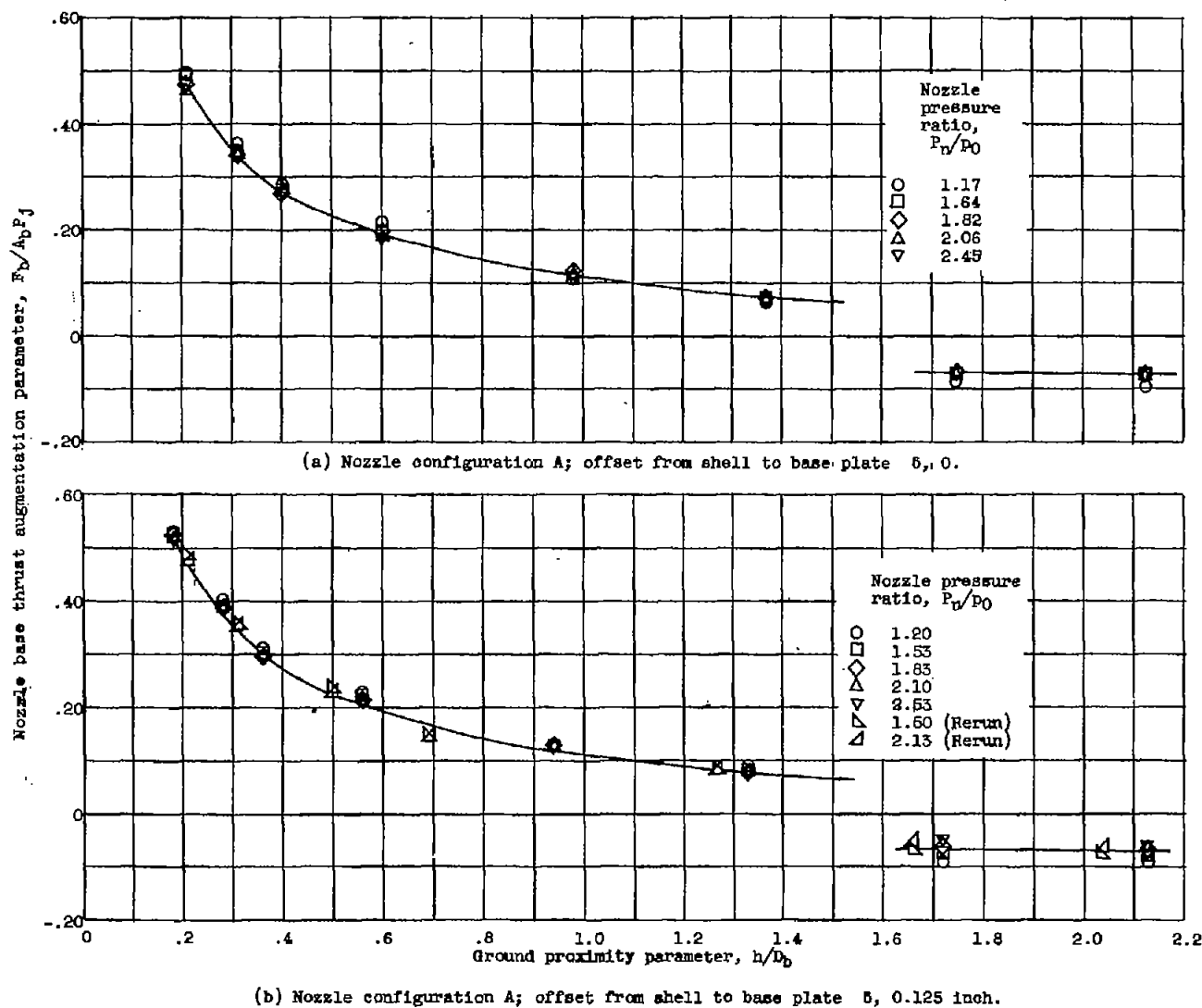
Figure 8. – Variation of thrust parameter determined from pressure integration over nozzle base with ground proximity parameter.

(c) Nozzle configuration A; offset from shell to base plate δ, 0.5 inch.

(d) Nozzle configuration B; offset from shell to base plate δ, 0.125 inch.
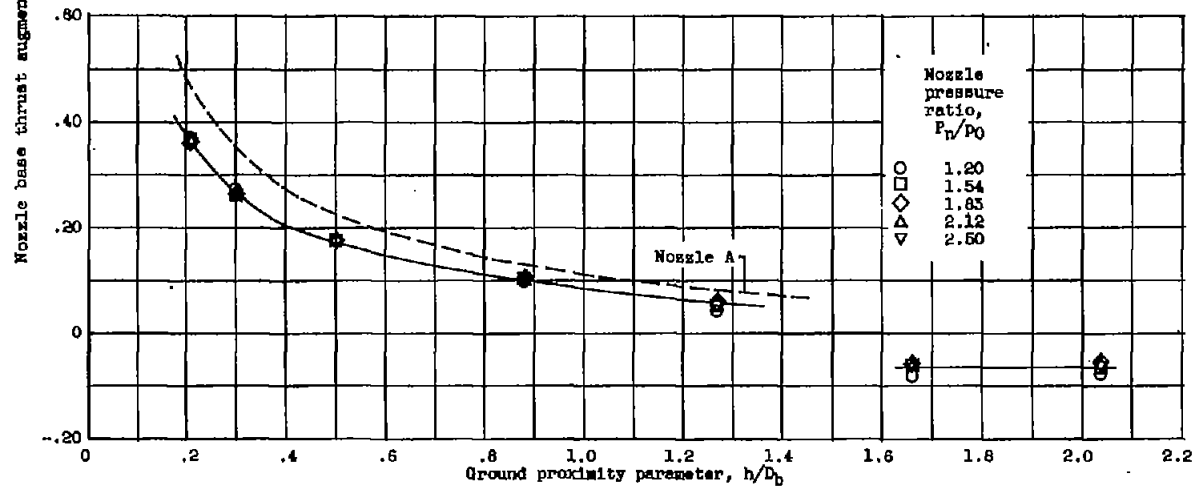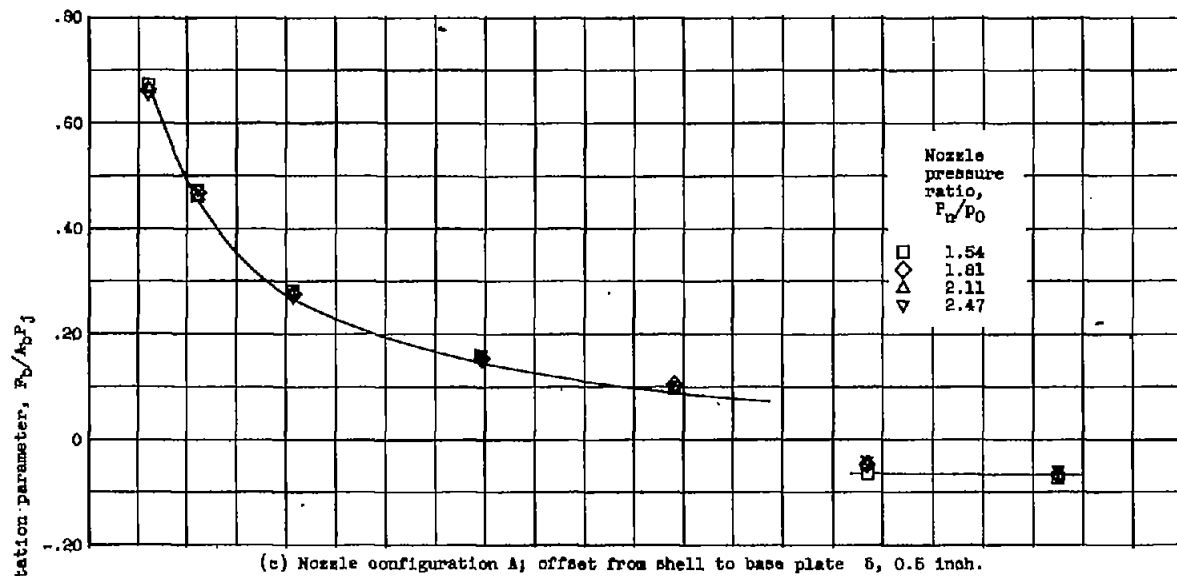
Figure 8. -- Continued.   Variation of thrust parameter determined from pressure integration over nozzle base with ground proximity parameter.
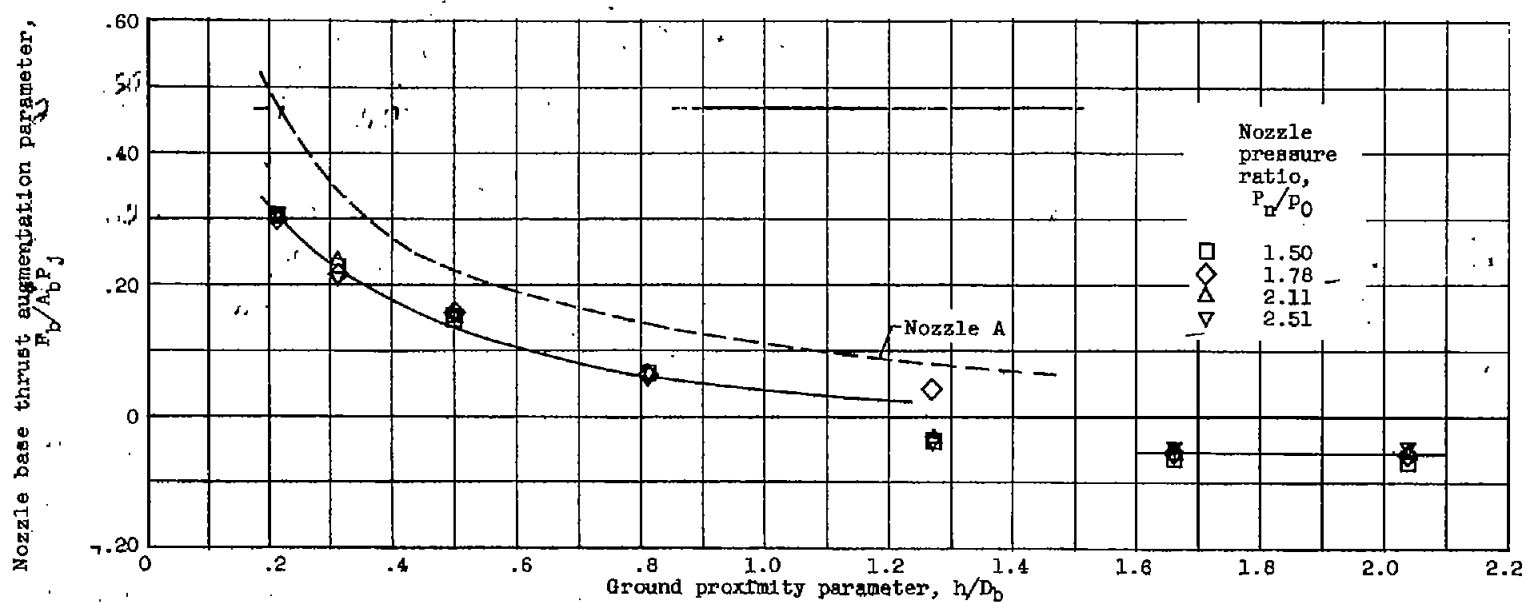
(e) Configuration C; offset from shell to base plate 8, 0.125 inch.

Figure 8. – Concluded. Variation of thrust parameter determined from pressure integration over nozzle base with ground proximity parameter.
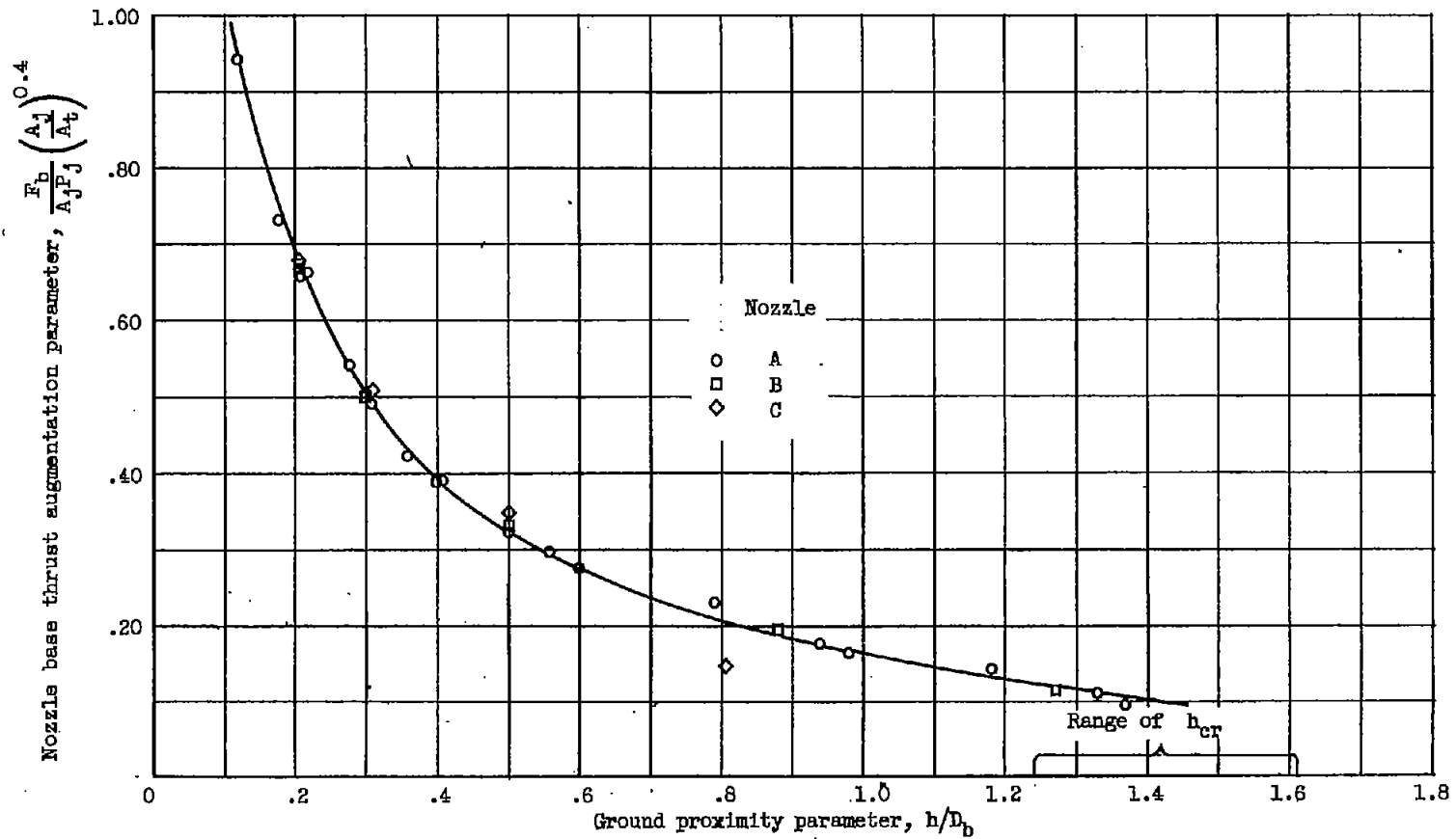
Figure 9. - Variation of thrust augmentation parameter $\frac{F_b}{A_j P_j}\left(\frac{A_j}{A_t}\right)^{0.4}$ with ground proximity parameter. Annular nozzles.
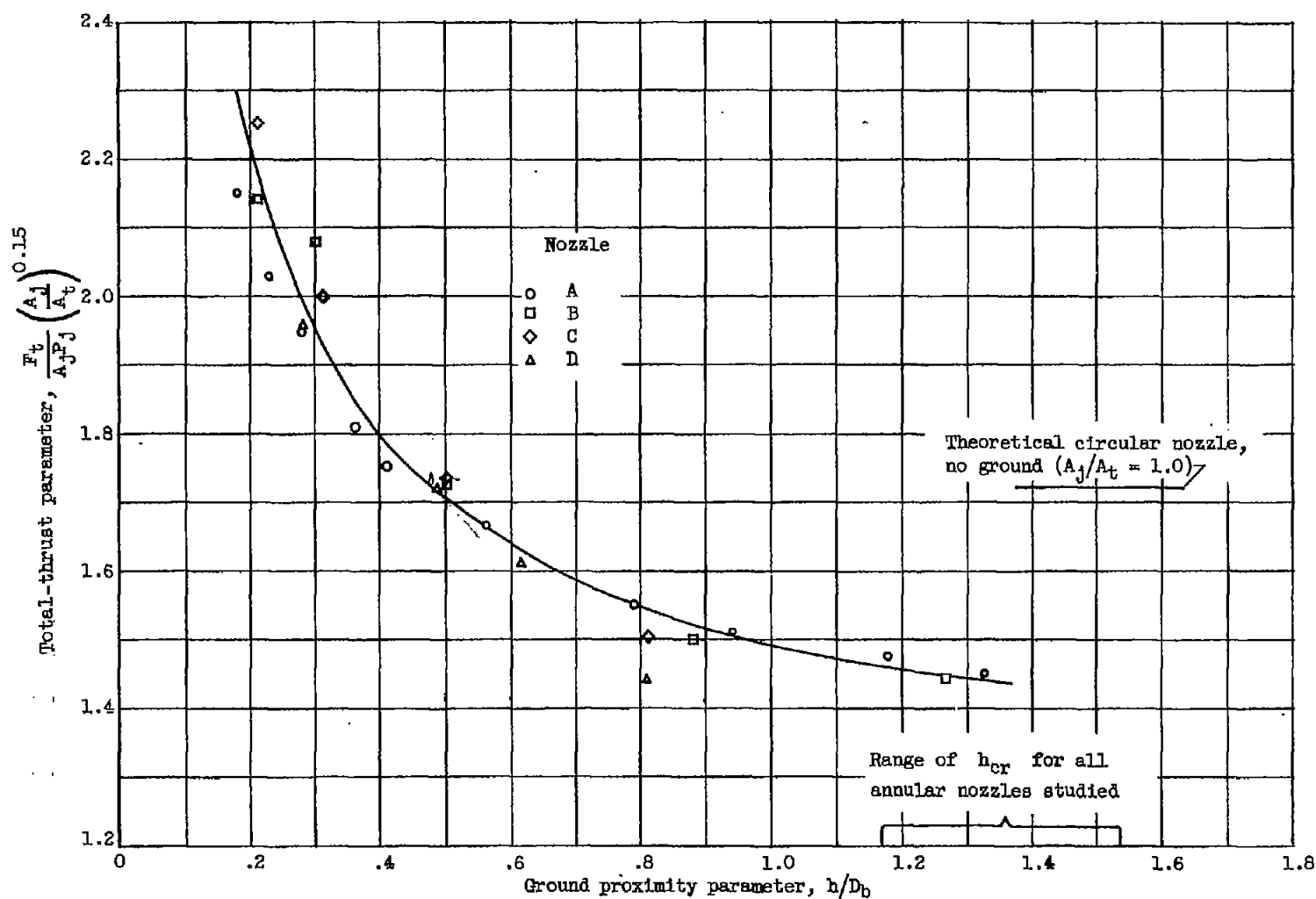
(a) Nominal nozzle pressure ratio, 1.5.

Figure 10. - Variation of total-thrust parameter with ground proximity parameter for several nozzle pressure ratios.
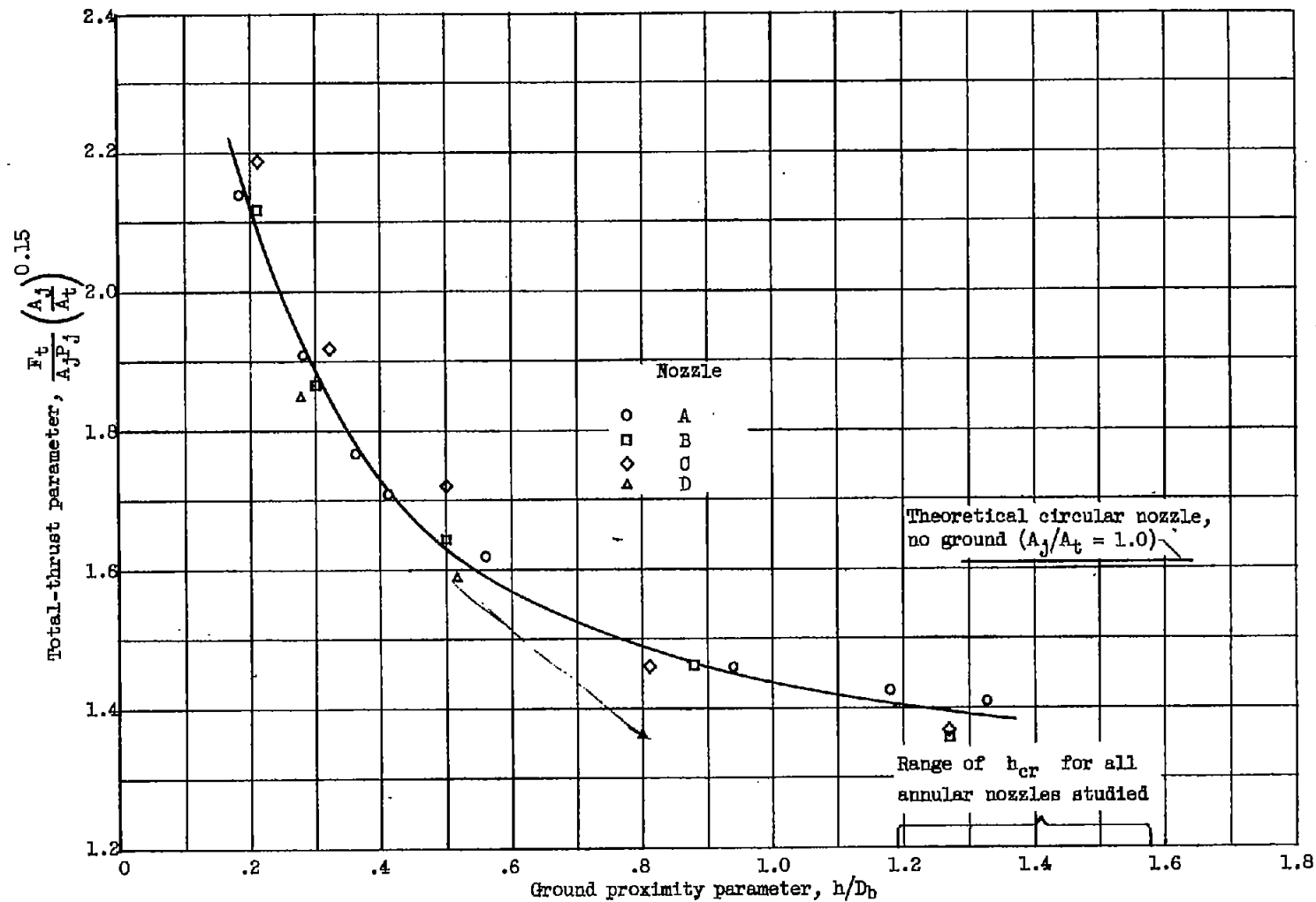
(b) Nominal nozzle pressure ratio, 1.8.

Figure 10. - Continued. Variation of total-thrust parameter with ground proximity parameter for several nozzle pressure ratios.
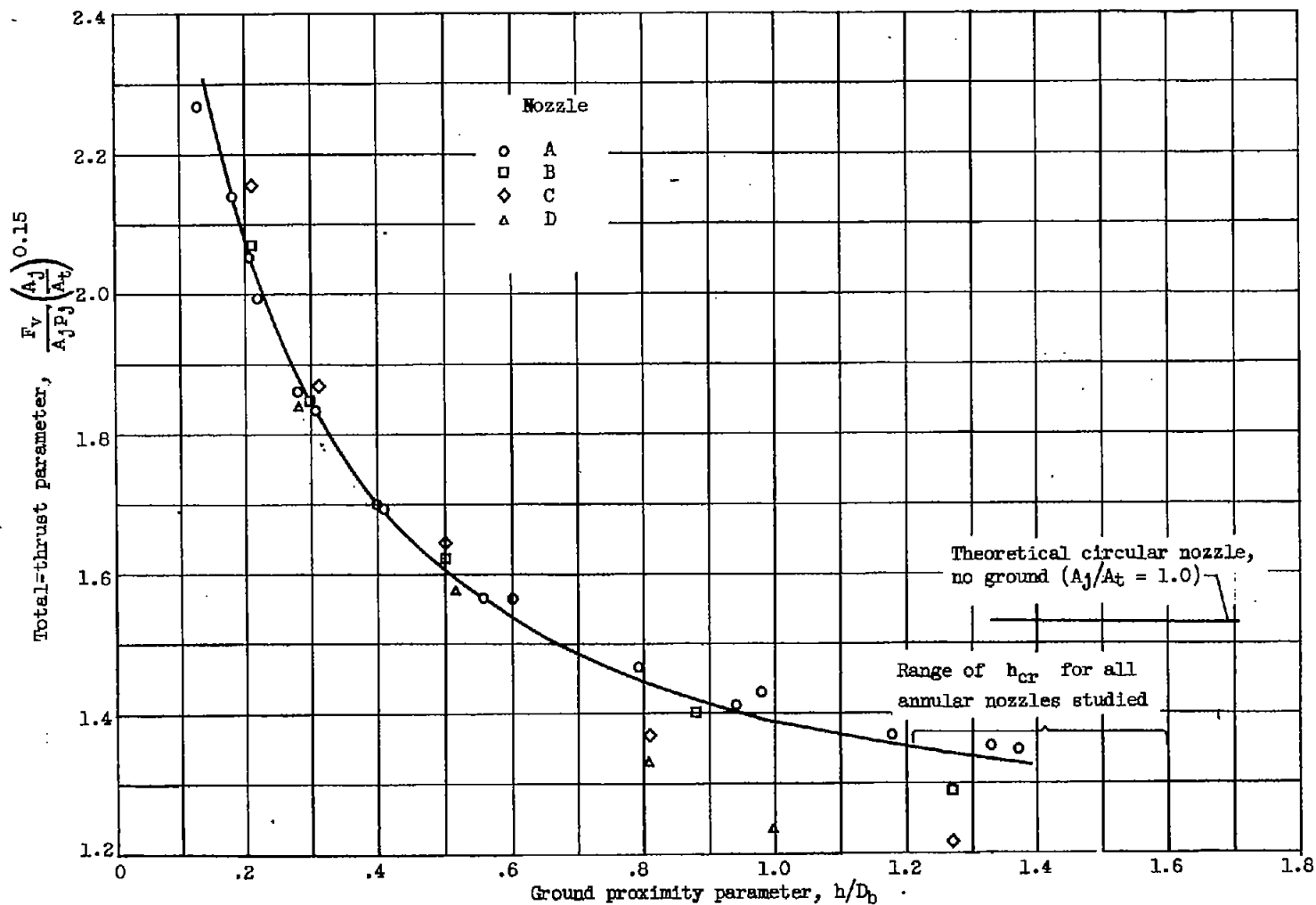
(c) Nominal nozzle pressure ratio, 2.1.

Figure 10. - Continued. Variation of total-thrust parameter with ground proximity parameter for several
nozzle pressure ratios.

Total-thrust parameter, $\dfrac{F_t}{A_j P_j}\left(\dfrac{A_j}{A_t}\right)^{0.15}$

Ground proximity parameter, h/D_b

Nozzle

○   A
□   B
◇   C

Theoretical circular nozzle, no ground ($A_j/A_t = 1.0$)

Range of h_{cr} for all annular nozzles studied
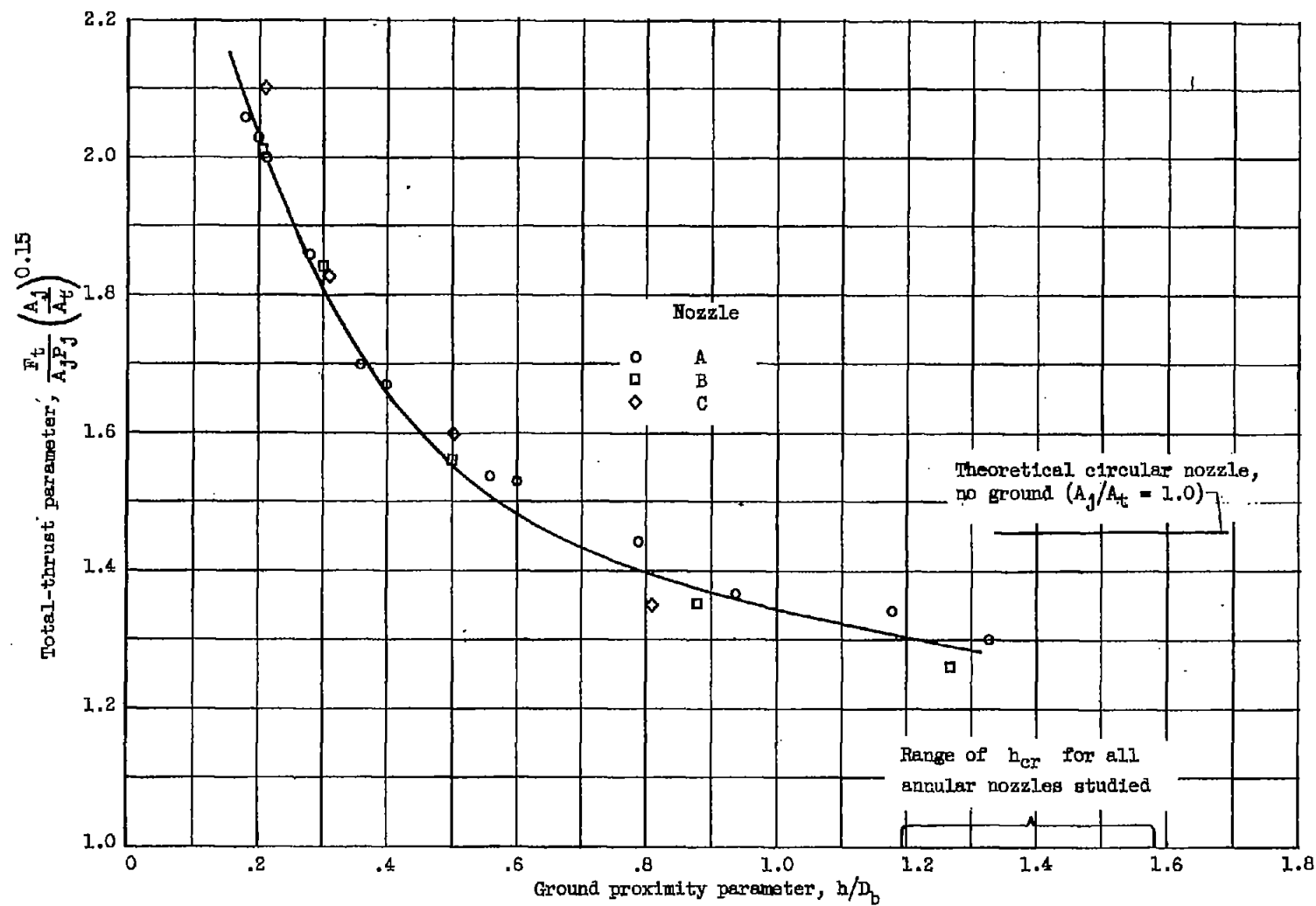
(d) Nominal nozzle pressure ratio, 2.5.

Figure 10. - Continued. Variation of total-thrust parameter with ground proximity parameter for several nozzle pressure ratios.
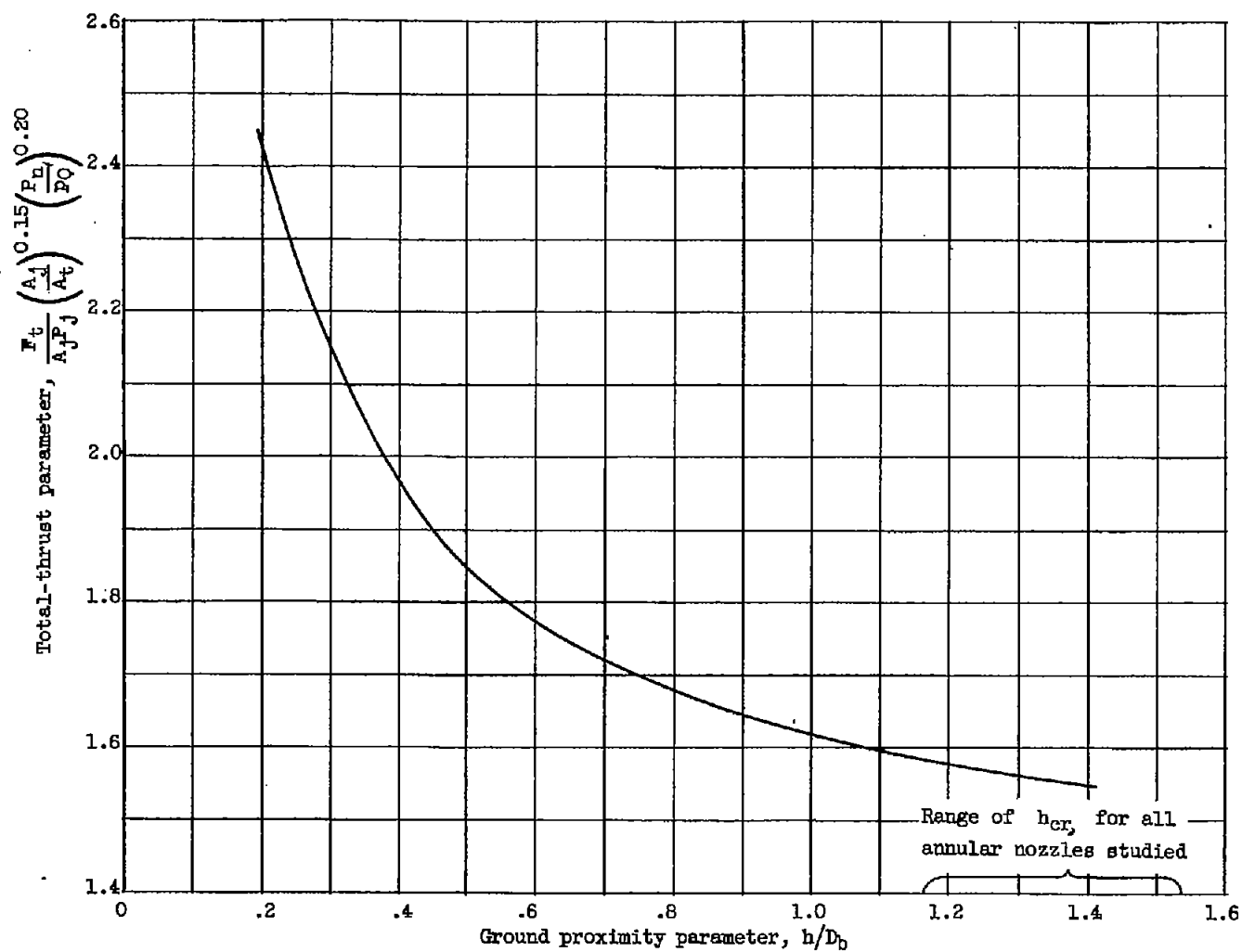
(e) Correlation of all nozzle pressure ratios based on faired curves of figures 10(a) to (d).

Figure 10. - Concluded. Variation of total-thrust parameter with ground proximity parameter for several nozzle pressure ratios.

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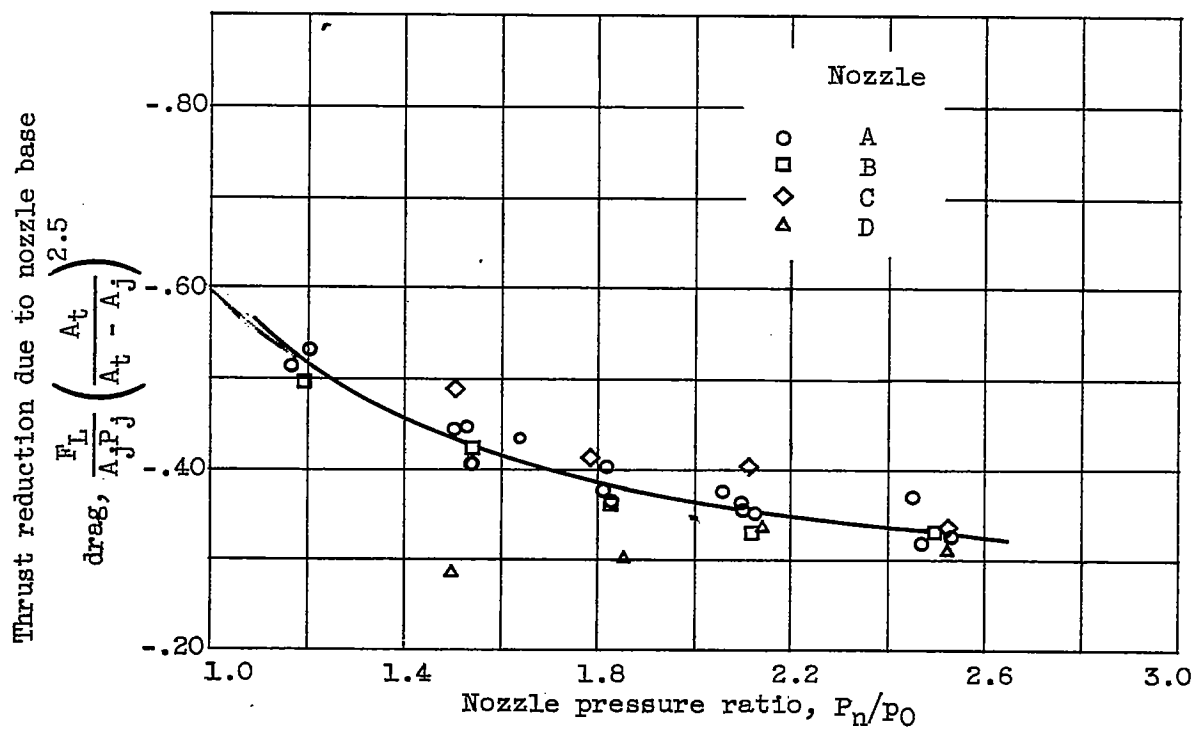
Figure 11. - Effect of nozzle pressure ratio on thrust loss for annular nozzle without ground effect.
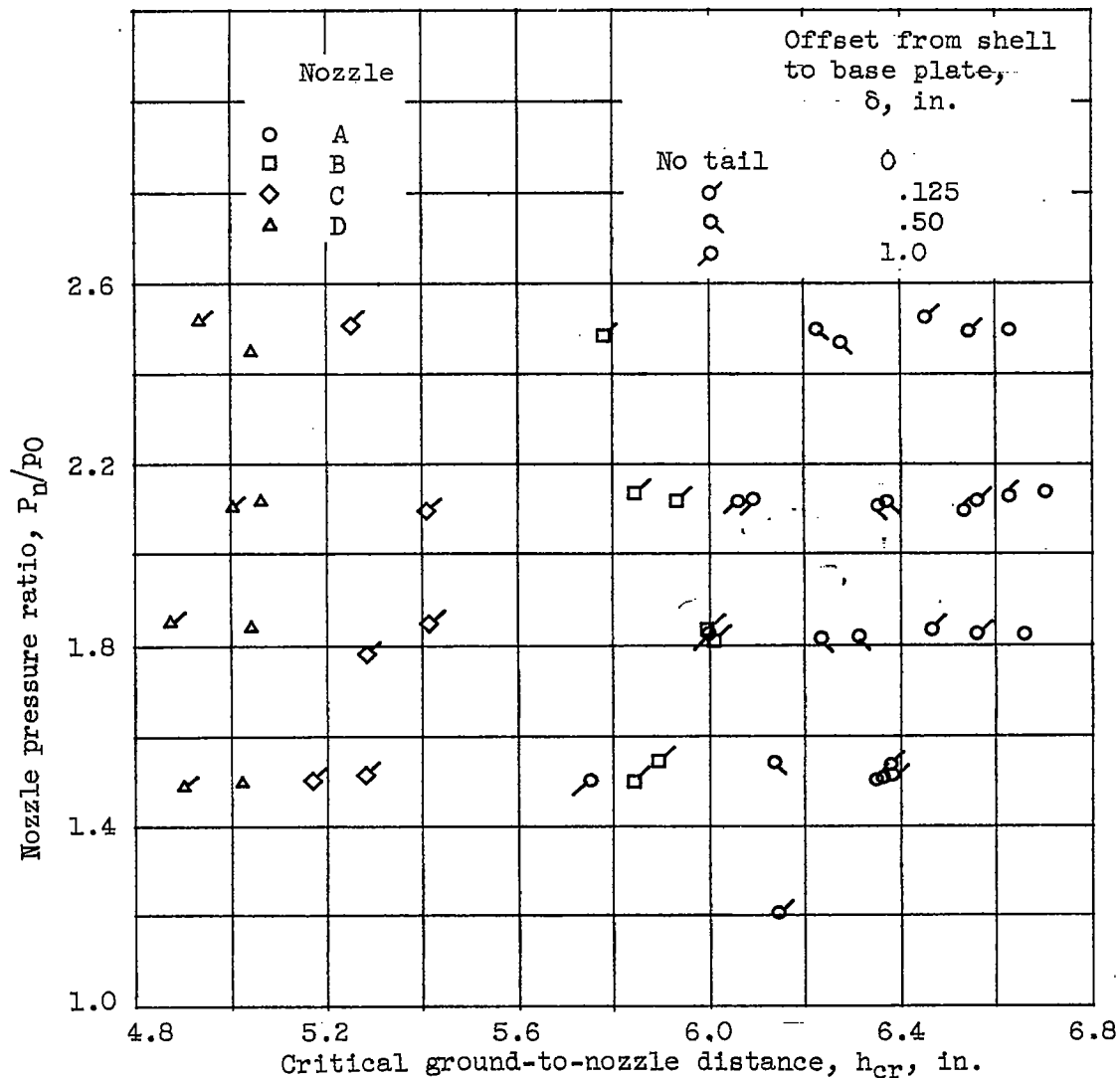
Figure 12. - Variation of critical ground-to-nozzle distance
at which thrust augmentation begins with nozzle pressure
ratio and nozzle configuration.

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CF-5 back
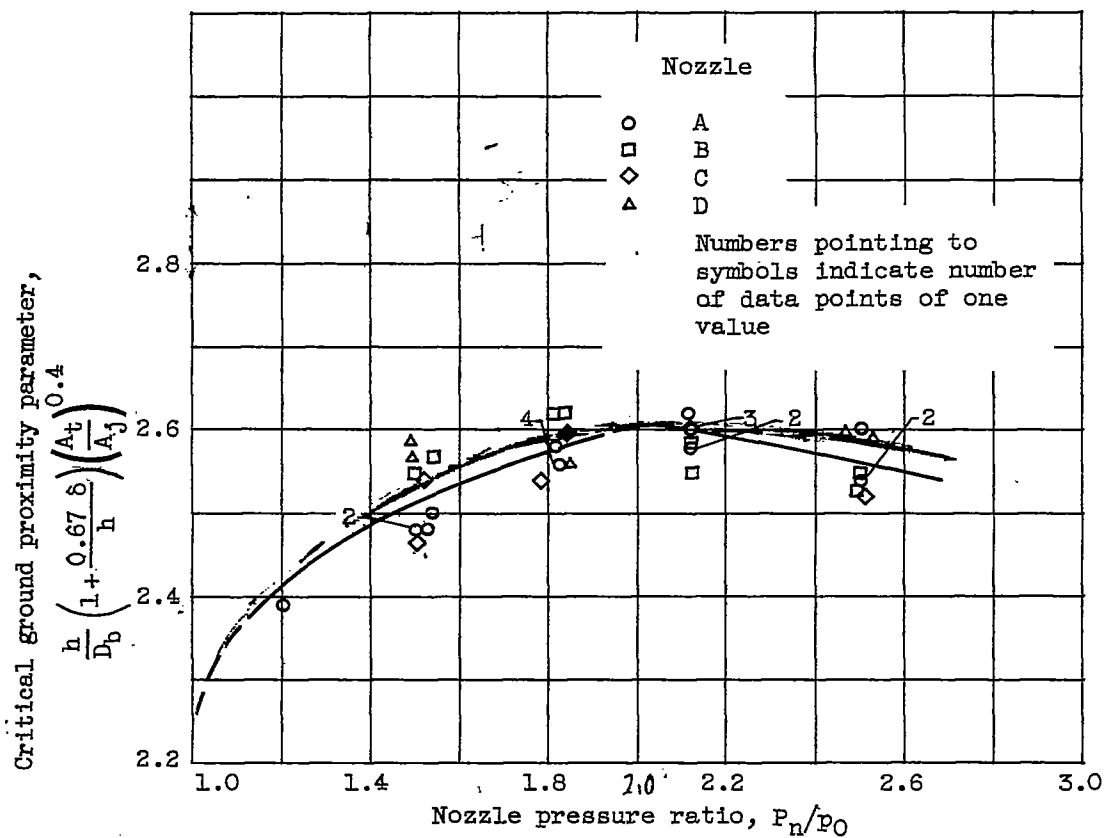
Figure 13. - Critical ground proximity parameter at which thrust augmentation begins as function of nozzle pressure ratio.
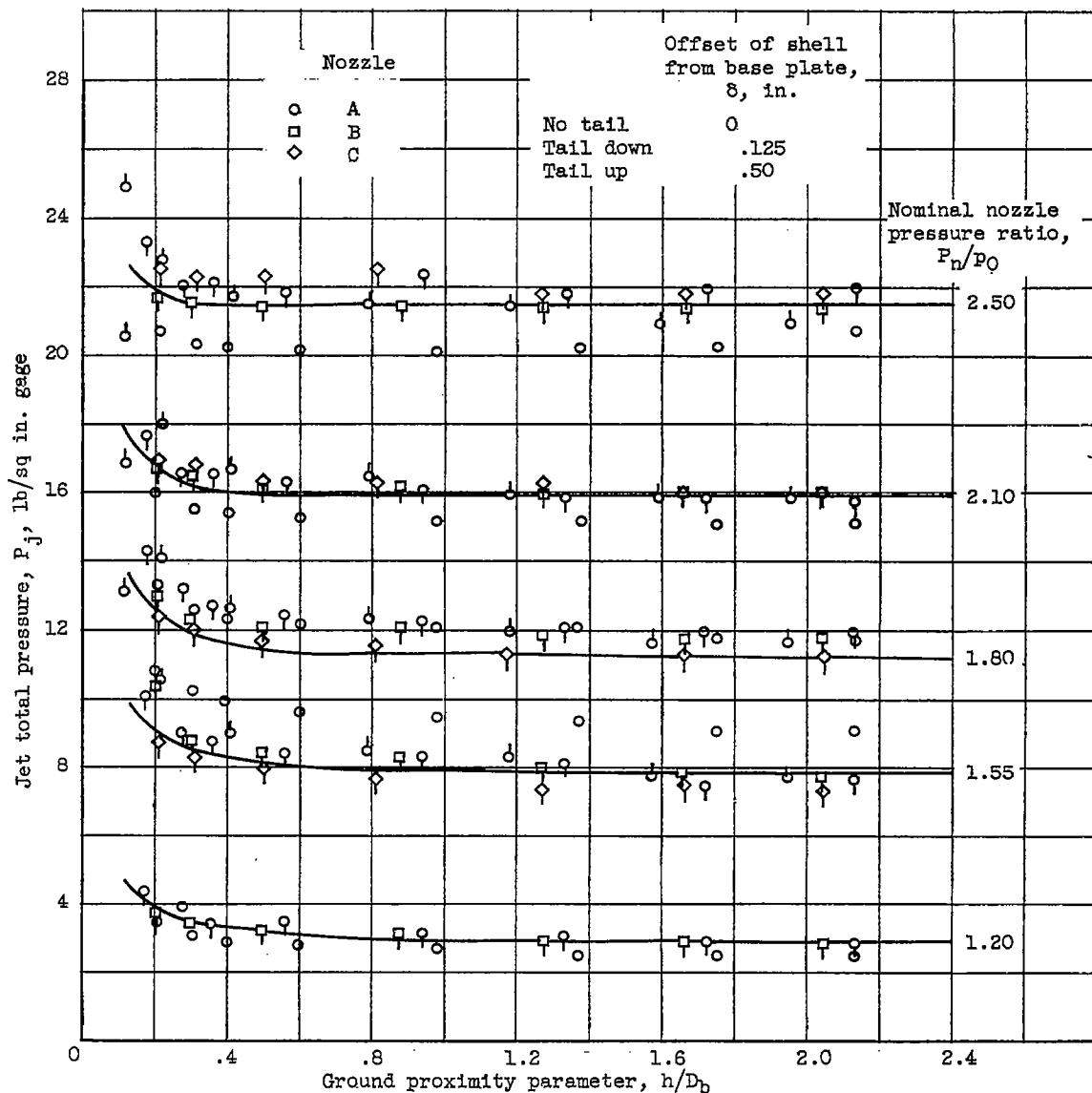
(a) Typical variation of P_j with ground proximity parameter for various pressure ratios.

Figure 14. - Effect of ground proximity on jet total pressure.

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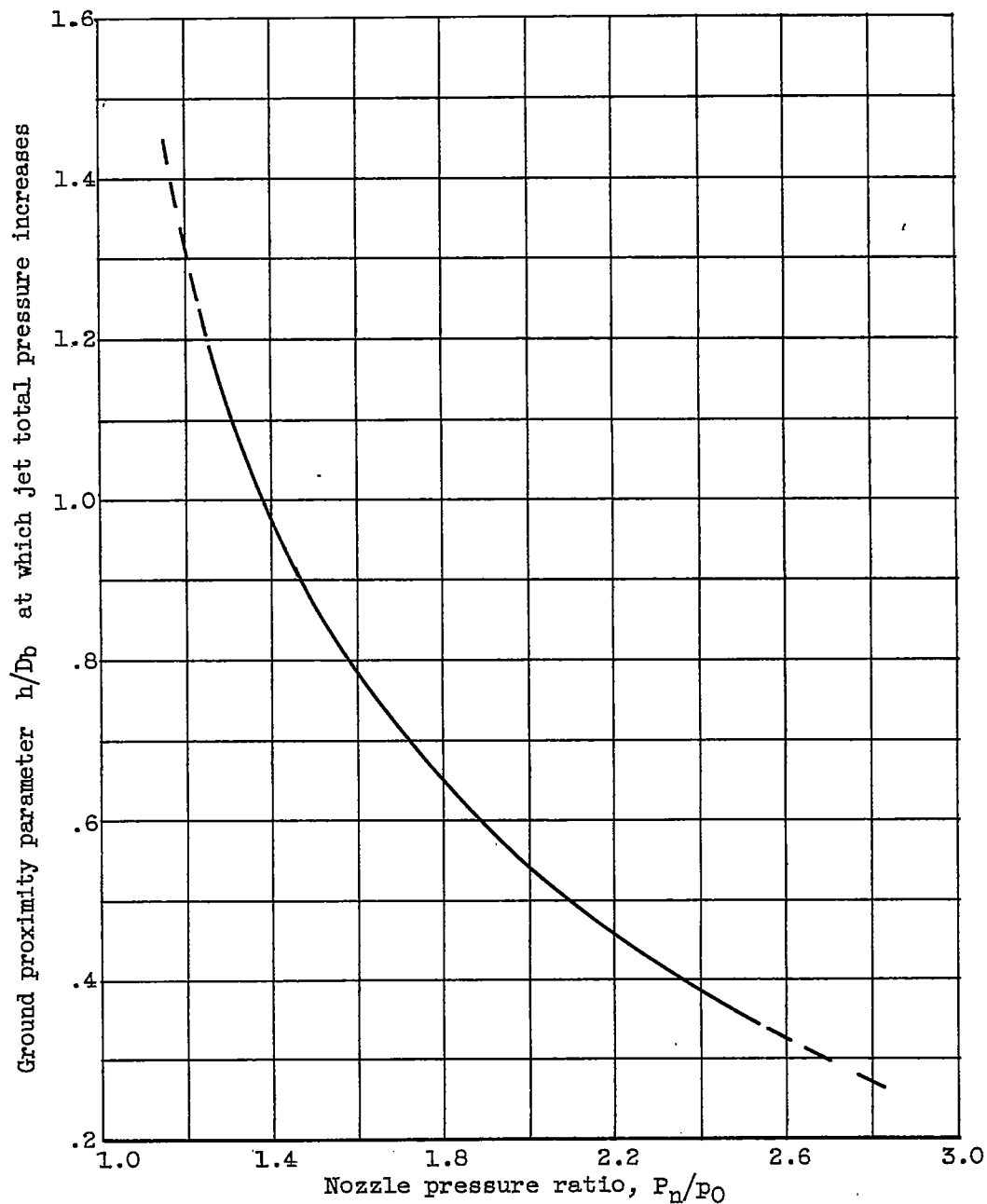
(b) Initial h/D$_b$ values at which jet total pressure increases
    as function of nozzle pressure ratio for nozzles A, B, and
    C.

Figure 14. - Concluded. Effect of ground proximity on jet total
    pressure.
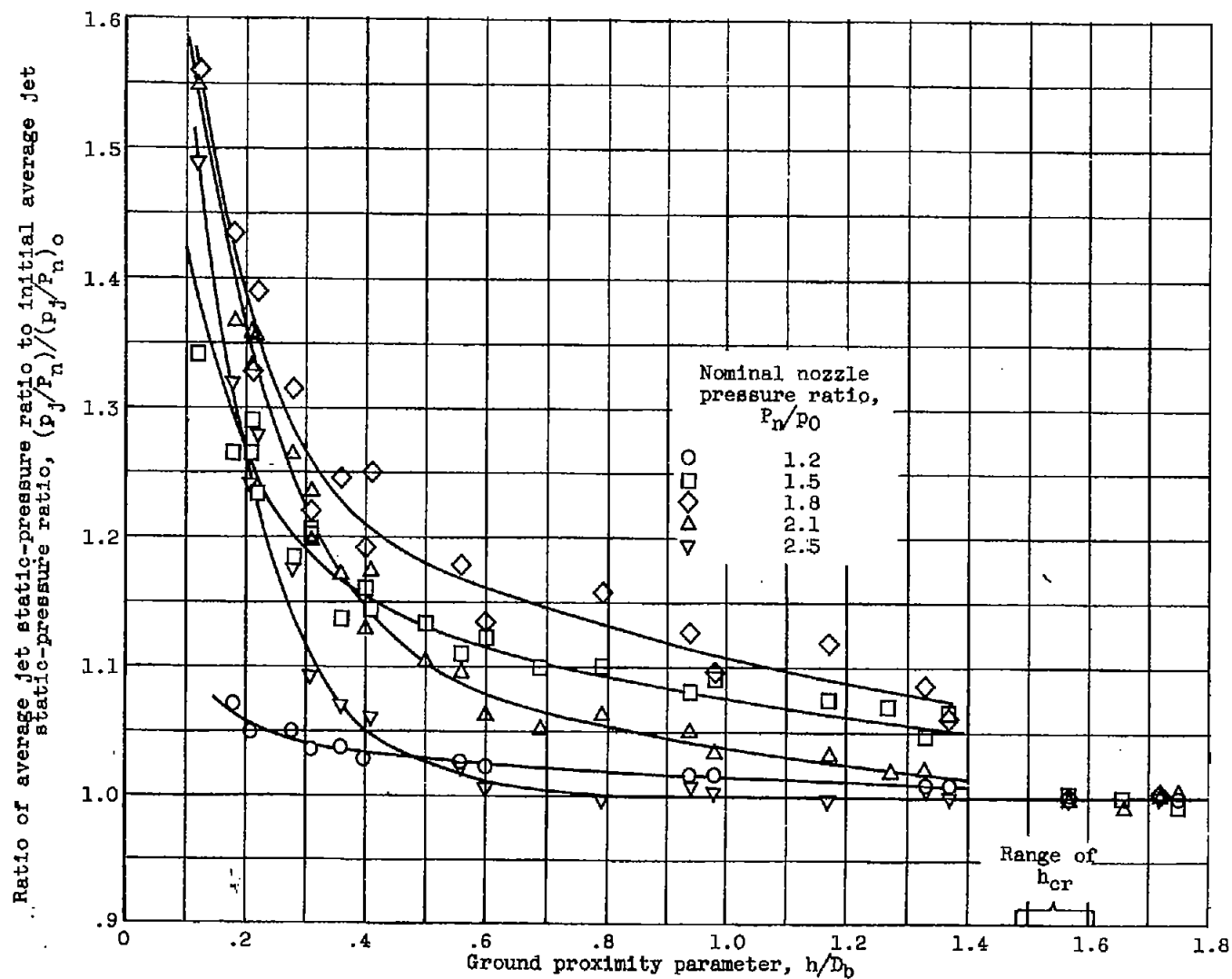
Figure 15. - Effect of ground proximity on jet static pressure. Nozzle A; offset of shell from base plate 5, 0, 0.125, and 0.5 inch.

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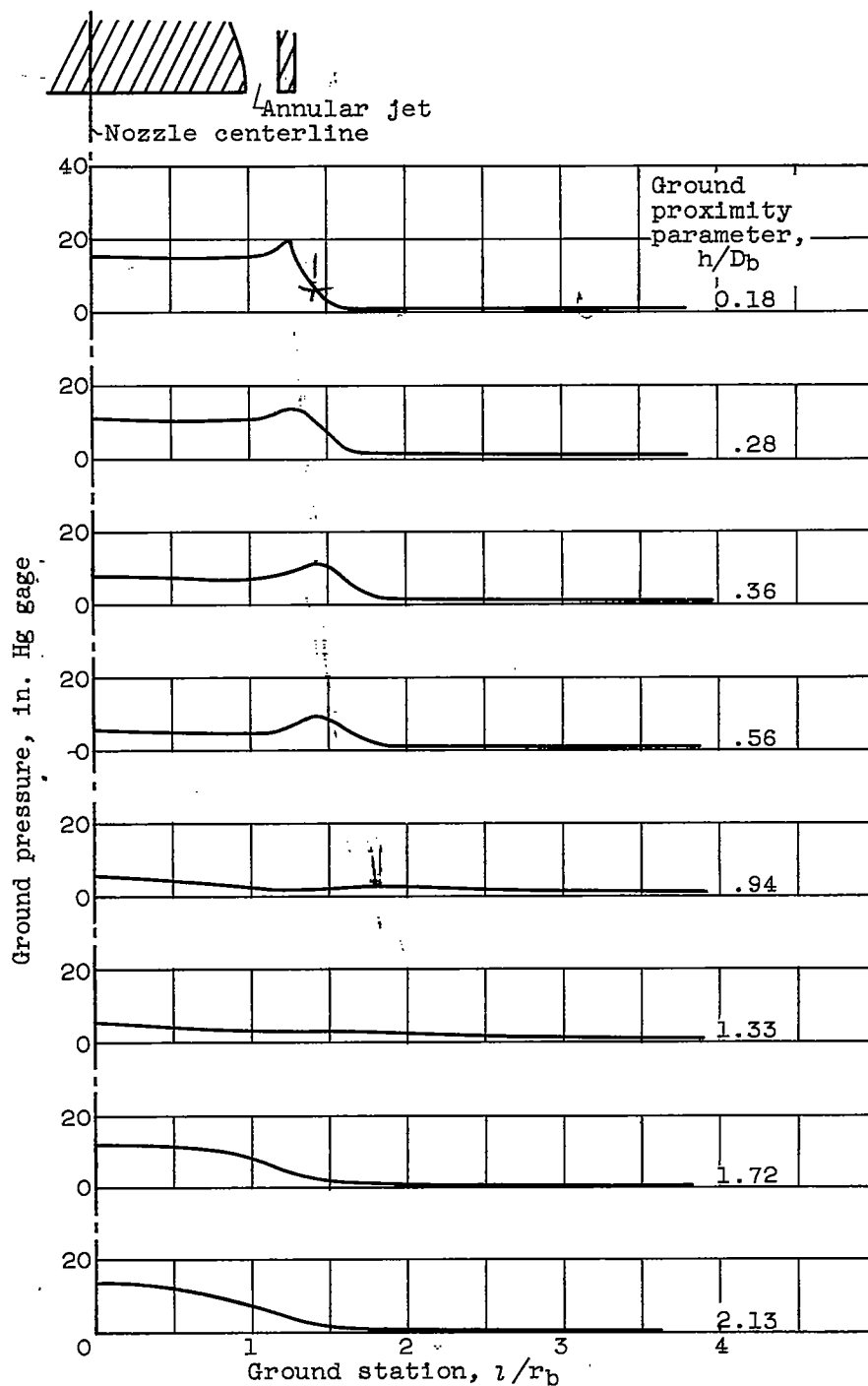
(a) Nozzle pressure ratio, 1.8.

Figure 16. - Effect of ground proximity of nozzle
   on ground pressure profile. Nozzle configuration
   A.
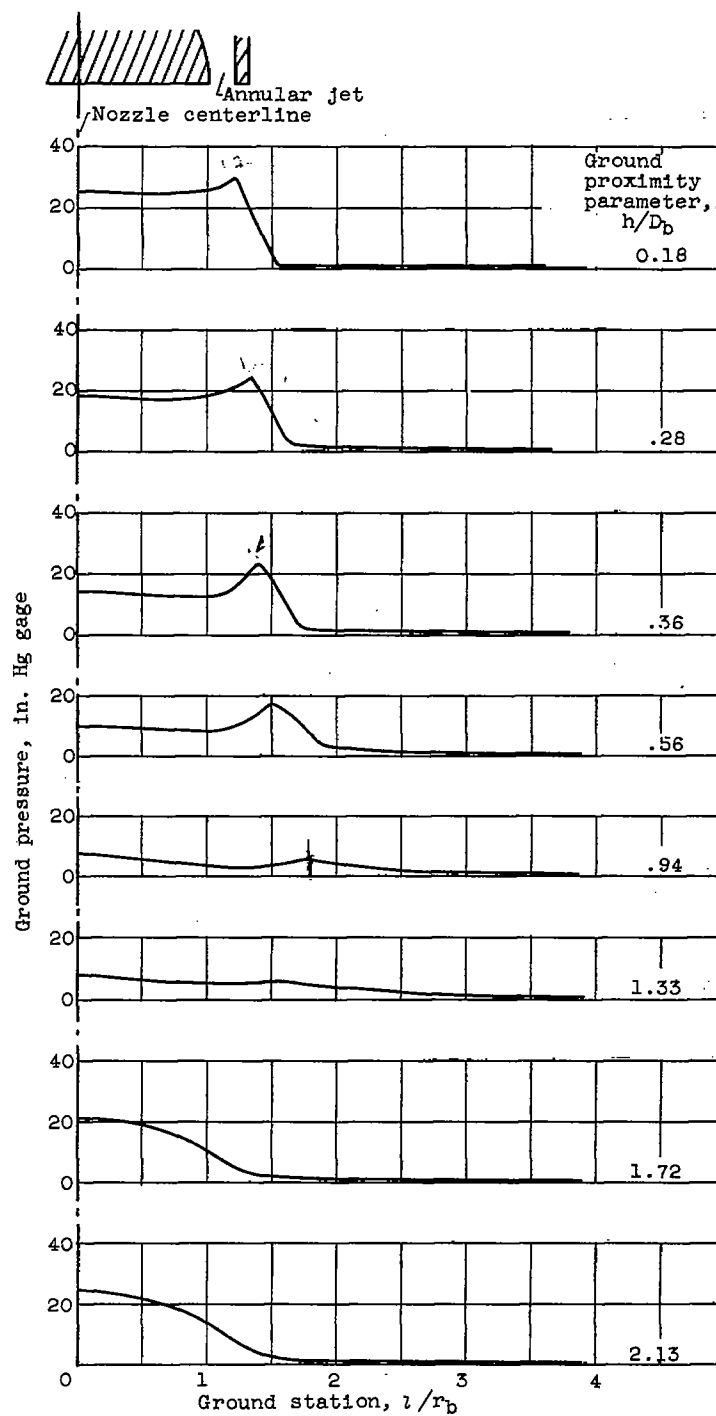
(b) Nozzle pressure ratio, 2.1.

Figure 16. - Concluded. Effect of ground proximity
of nozzle on ground pressure profile. Nozzle
configuration A.
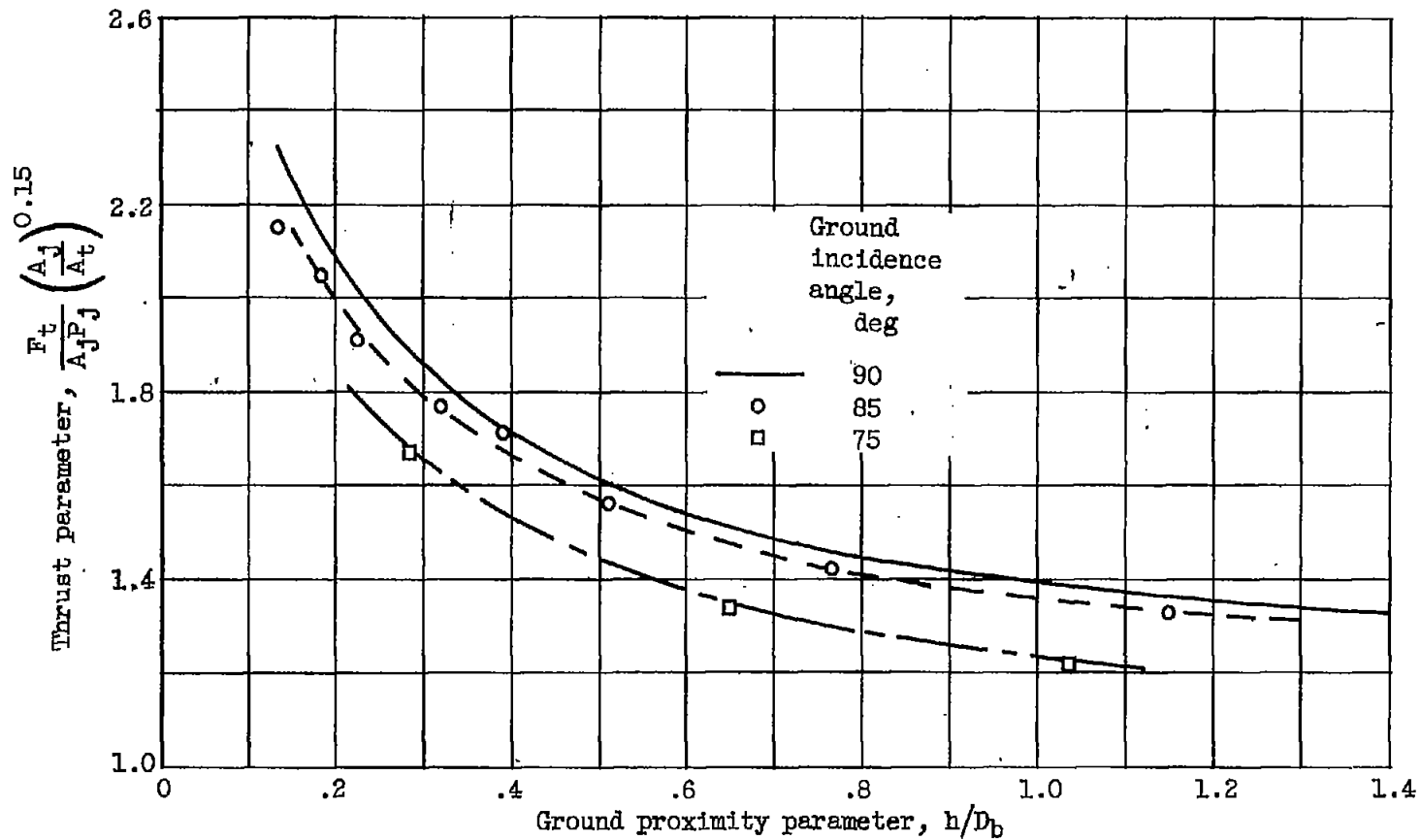
Figure 17. - Effect of ground incidence angle on thrust of annular nozzle. Nozzle configuration A; nozzle pressure ratio, 2.1.
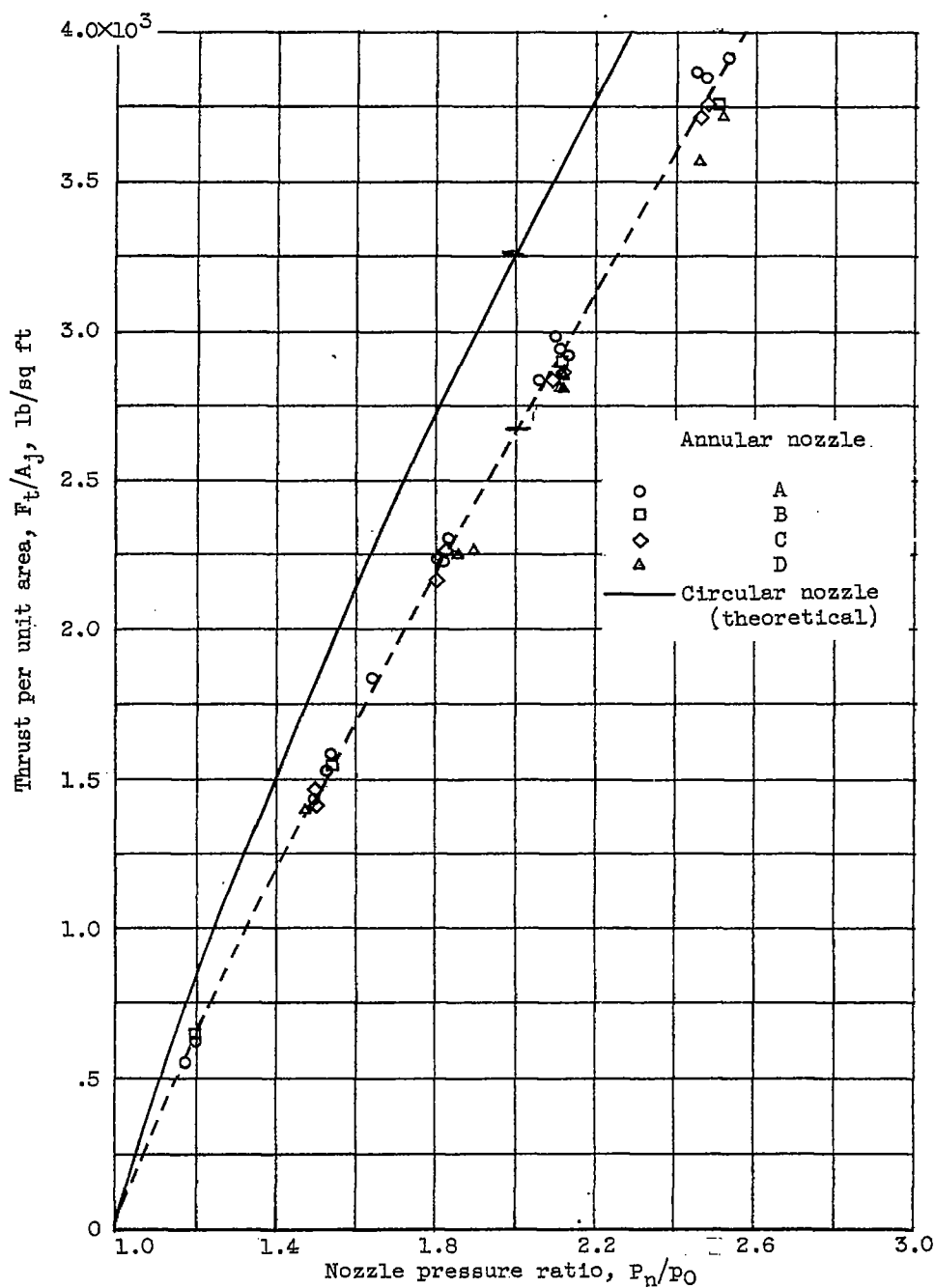
(a) F_t/A_j against P_n/p_0.

Figure 18. - Comparison of thrust without ground effect for
annular nozzle with theory for circular nozzle. Atmospheric
pressure for circular-nozzle calculation, 2116 pounds per
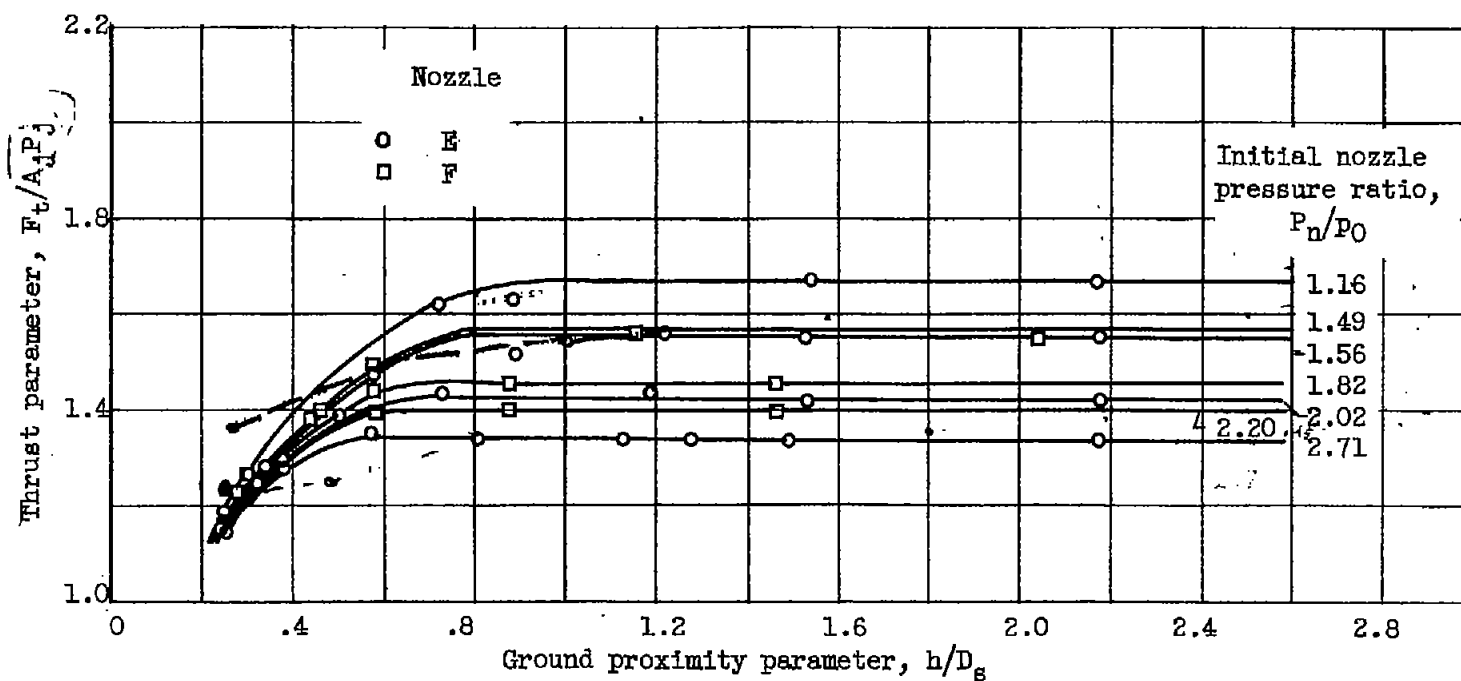square foot.

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CF-6 back
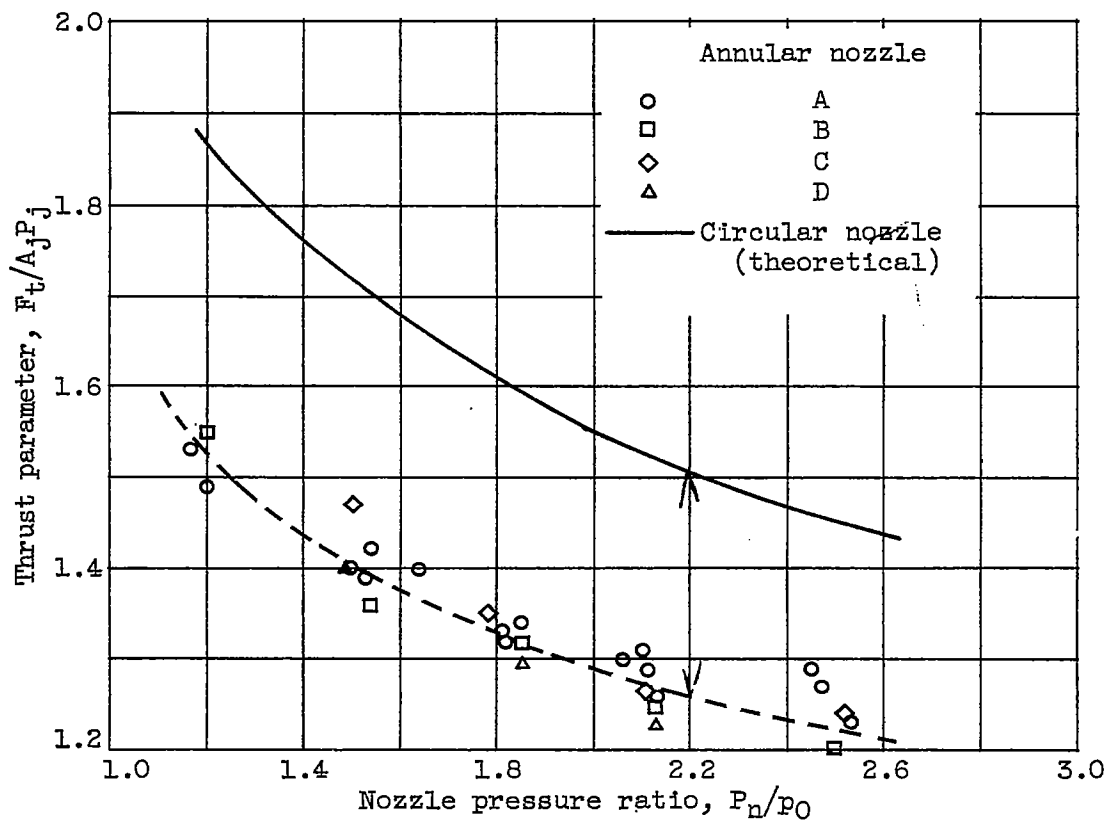
(b) F_t/A_jP_j against P_n/p_0.

Figure 18. - Concluded. Comparison of thrust without ground
effect for annular nozzle with theory for circular nozzle.
Atmospheric pressure for circular-nozzle calculation, 2116
pounds per square foot.

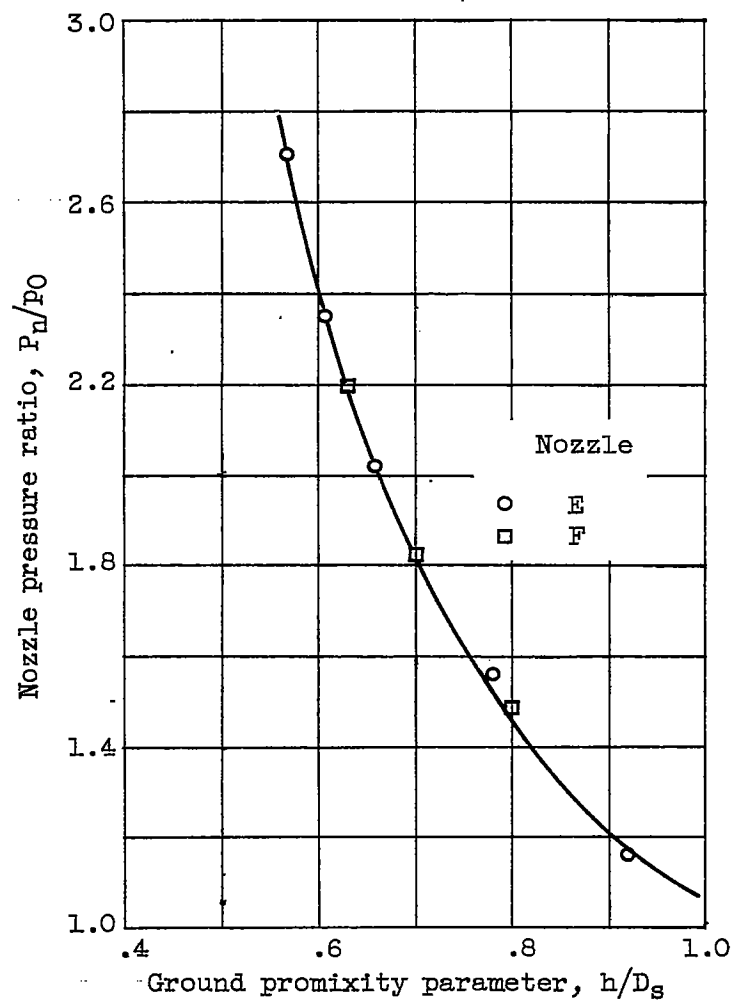Figure 19. - Effect of ground proximity on thrust of circular nozzle.

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Figure 20. - Effect of nozzle pressure
ratio on ground distance at which
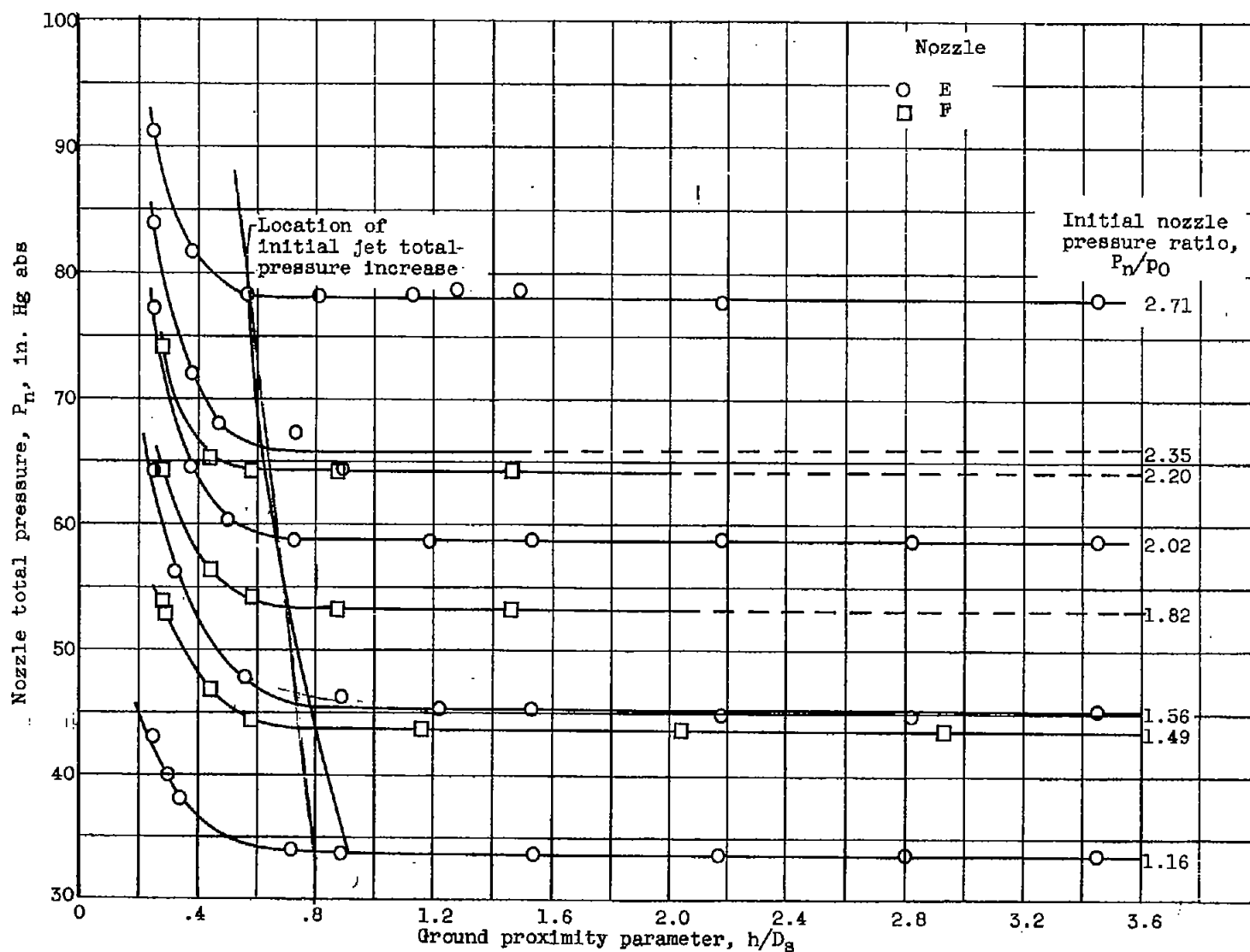thrust losses occur with circular
nozzle.

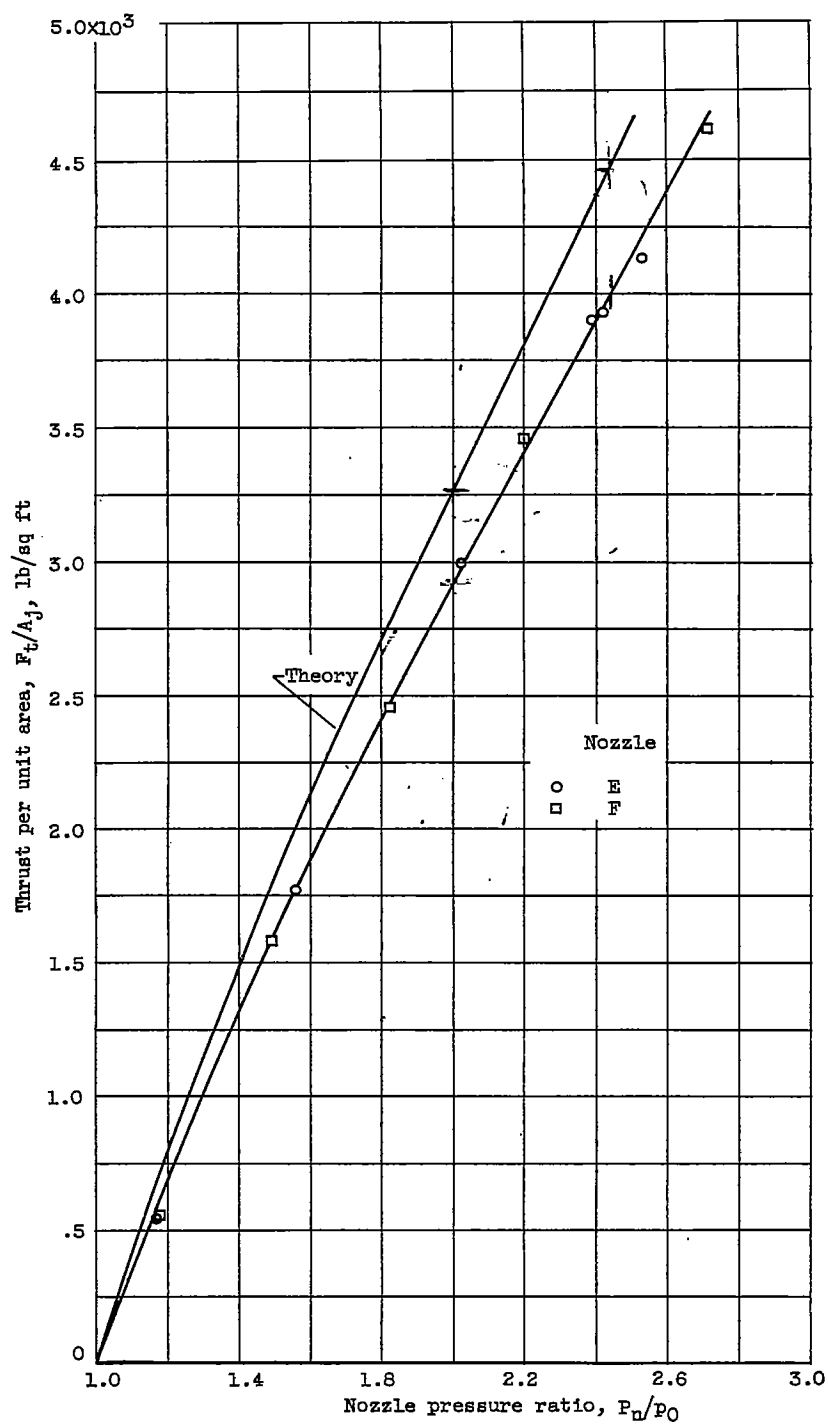Figure 21. - Effect of ground proximity on jet total pressure for circular nozzle.
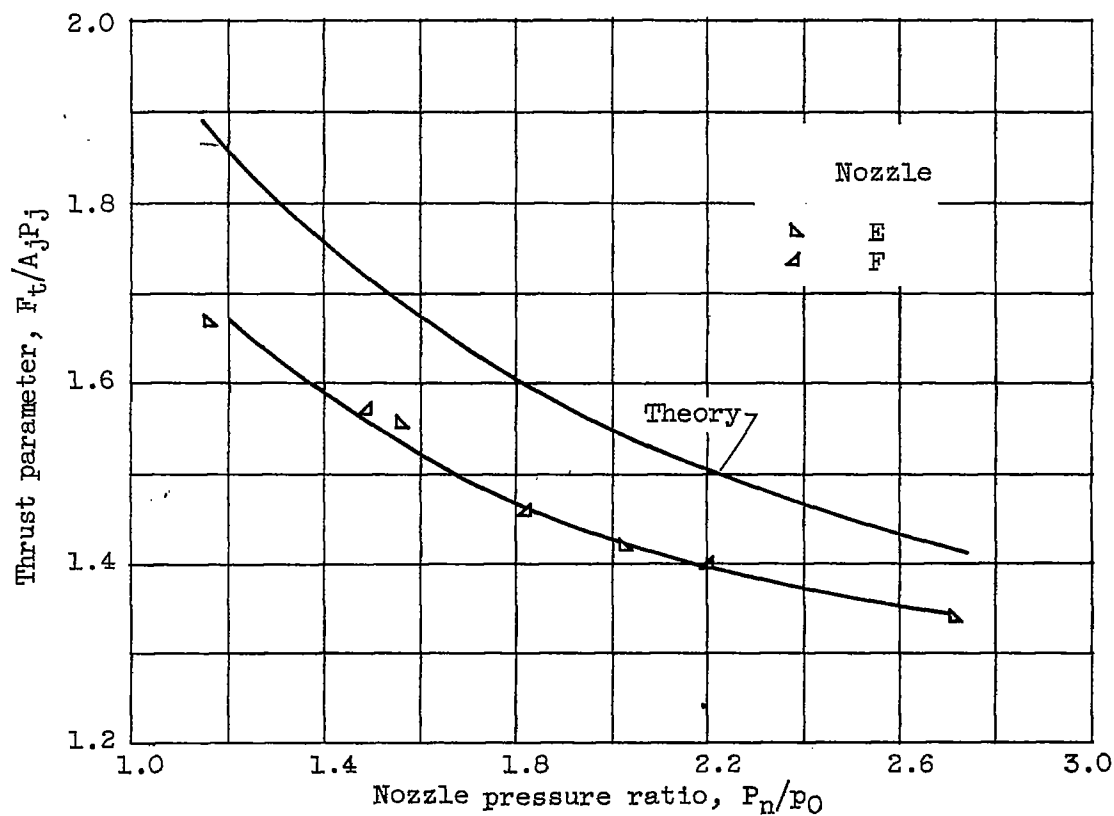
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(a) F_t/A_j against P_n/p_0.

Figure 22. - Comparison of theoretical and experimental thrust
values for circular nozzle discharging into still air.

(b) F_t/A_jP_j against P_n/p_0.

Figure 22. - Concluded. Comparison of theoretical and experimental thrust values for circular nozzle discharging into still air.